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Using rainfall simulation and tracer anions to study the effects of soil bulk density and soil moisture on nitrate leaching characteristics

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ABSTRACT

Nitrogen (N) fertilizers applied to cropland are of considerable importance because of the yield-increasing benefits they provide. However, potential nitrate-nitrogen (NO_3-N) leaching losses with subsurface drainage are of considerable concern, particularly in the Midwest. Because rainfall and irrigation amounts typically exceeds the annual evaporative demands in this region, drainage to ground water or surface water (via tile drainage) can result in N movement out of the root zone. A laboratory experiment was conducted to study the effects of soil bulk density in the zone of N application and soil moisture on NO_3-N leaching from surface soils during rainfall simulation using tracer anions. Simulated rainfall was applied at an intensity of 6.5 cm h^{-1} for 70 min to soil pans with compacted soil bars of 1.10, 1.33, 1.57, and 1.81 g cm^{-3} bulk density and initial soil moisture contents of 10 and 15% by mass. Surface runoff, subsurface drainage, and soil extract samples were analyzed for NO_3-N, bromide (Br), and chloride (Cl) concentrations.

Surface runoff losses of NO_3-N and Br were greater at 15% moisture content because of greater runoff volumes. Higher bulk density in the zone of N application resulted in significantly lower concentrations and losses of NO_3-N in subsurface drainage. The 10% moisture content produced greater NO_3-N leaching losses due to greater volume of subsurface drainage at that moisture. A NO_3-N mass balance indicated that higher bulk density and moisture content resulted in retention of greater amounts of NO_3-N in the soil. Bromide concentrations and losses and Cl losses in subsurface drainage were lower at 15% moisture content. From the research results, it seems that compacting soil within the zone of N fertilizer application can significantly reduce NO_3-N losses to subsurface drainage. Future research could involve examining compaction on the field scale and improving an actual N

applicator. Soil compaction up to 1.81 g cm^{-3} could be reached by field applicator. Since higher soil moisture helped to reduce NO_3-N leaching, the amount of liquid associated with the N fertilizer might be a consideration if handling larger volumes was not an obstacle.

CHAPTER 1. GENERAL INTRODUCTION

Introduction

Groundwater is an important natural resource whose quality can directly affect many people. In the U.S., groundwater is the source of about 22% of the fresh water used. About 53% of the total population and 97% of the rural population use groundwater supplies for their drinking water (Moody, 1990). Although contamination of groundwater can occur naturally, agriculture is considered one of the most widespread nonpoint sources of groundwater contamination. Among all the agricultural chemicals that have the potential to contaminate groundwater, nitrogen (N) applied as fertilizer and manure is the most extensively used, especially by corn producers (Kiuchi et al., 1996). About one million tons of N fertilizer are used annually in Iowa.

Bouwer (1990) reported that nitrate (NO_3) is the main form of N in soil taken up by plants. He further noted that NO_3 is very mobile in the underground environment and moves readily with deep percolation through the vadose zone to underlying groundwater. Thus, applied N not used by crops, and not lost by runoff or denitrified or volatilized, either is stored in the soil as organic-N or eventually reaches underlying groundwater (Bouwer, 1990). Contamination of surface water by N fertilizers via tile drainage is of concern too. In some studies, more than 50% of the applied N is not removed by the crop or stored in the soil, and NO_3-N leaching is thought to be a major reason for these losses (Blackmer, 1987). Nitrate-nitrogen concentrations in vadose-zone water below agricultural fields typically are in the range of 5 to 100 mg L^{-1}, with frequent detections of concentrations of 20 to 40 mg L^{-1} (Bouwer 1990). This NO_3-N eventually may enter groundwater supplies. The maximum

contamination level (MCL) for drinking water is 10 mg L^{-1}. Too much NO_3-N in drinking water can cause methemoglobinemia, or blue-baby disease, in infants.

Nitrogen as fertilizers and manures is widely used in corn production in the north-central region of the U.S. Because rainfall and irrigation amounts typically exceed the annual evaporative demands in this region, drainage to ground water or surface water (via tile drainage) can result in N movement out of the root zone. Koplin et al. (1991) reported that 6% of 566 samples collected from 303 shallow wells in midwestern U.S. had NO_3-N concentrations that exceeded the 10 mg L^{-1} MCL. Groundwater provides a significant component of the total flow in many midwestern rivers and streams, and, where they exist, subsurface tile drains can transport NO_3-N from agricultural soils to waterways. Baker et al. (1975) have shown that NO_3-N in tile drainage water from row-crop land usually exceeds 10 mg L^{-1}, with annual leaching losses averaging more than 20 kg ha^{-1}. When this water is not intercepted by tile drains, but instead percolates to groundwater, contamination can occur there. When drainage from the root zone is intercepted by tile drains and short-circuited back to surface waters, contamination occurs there.

Manure N application is wide spread throughout Midwest, however, since the research reported here mainly focuses on fertilizer N applications, review of literature on manure N was omitted. Nitrogen fertilizers applied to cropland are of considerable importance because of the yield-increasing benefits they provide. However, cost and energy use for large quantity applications, potential NO_3-N leaching losses to water resources, and associated farmer and societal costs attached to such losses are of considerable concern, particularly in the Midwest. Currently, in the Corn Belt, fertilizer N usually is applied in a single preplant application as anhydrous ammonia (NH_3) in the fall or in early spring, as

granular urea, or as a urea ammonium nitrate (UAN) solution. This N is susceptible to loss once the soil warms and nitrification of NH_3 to NO_3 takes place. Baker et al. (1989) reported that there are at least four ways that N can be lost from the soil crop systems: volatilization, loss in surface runoff, denitrification, and NO_3-N leaching; crop uptake is the major removal process.

Fertilizer losses represent economic and energy losses and can result in water quality deterioration. Current methods of fertilizer incorporation, either through tillage or through subsurface knife application, require tractive energy, and in addition, bury or destroy soil-protecting surface crop residue. Nitrate-nitrogen, because of its soluble and nonadsorbed nature, will move with water through the soil profile. Losses are a product of concentration and volume of leaching water. Several management strategies have been proposed to reduce N leaching from agricultural lands. One recent strategy is to divert the flow of infiltrating water away from or around the "zone" of applied N fertilizer. In a practical way, the route of water movement relative to the location of an anion like NO_3-N might be altered through localized compaction at the point of anion application. Such an approach was taken by Baker et al. (1997) as one way to alter water flow in soil by compacting the soil above applied fertilizer. A modified surface configuration combined with fertilizer placement in a zone away from substantial vertical water movement should help to minimize NO_3-N leaching. Similarly, subsurface water-flow barriers can reduce anion leaching. Studies have indicated, in theory, that the presence of a localized, impermeable subsurface barrier should direct infiltrating water away from the barrier and reduce the flow rate in the vicinity of the barrier. Soil compaction destroys the large voids and channels that may readily conduct rainwater in the upper soil profile. The reduced porosity of compacted soil makes it difficult for water to

infiltrate (Reicosky et al., 1981; Ankeny et al., 1990). If compaction occurs in localized zones, much of the infiltrating water is directed away form the compacted soil zone and toward more permeable, uncompacted soil. Further, water flow just above and below the compacted soil layer should be reduced. Thus, it is conceivable that NO_3-N leaching could be reduced if the fertilizer is placed in a "low-flow" region just above, below, or within such a barrier.

The overall purpose of this research was to study the effects of soil bulk density in the zone of N application and soil moisture content on NO_3-N leaching during laboratory rainfall simulation by use of tracer anions. Specifically, simulated rainfall with Br dissolved in it was applied to soil in pans of two different soil moisture contents and that had been treated with Cl. Compacted soil bars of four different bulk densities were placed within the soil in pans at 1.5 inches below the soil surface to achieve the following objectives:

1. To study the impacts of two levels of soil moisture and four levels of bulk density on the leaching characteristics of NO_3-N.
2. To use this information to help development/improvement of N application methods/equipment.

Thesis Organization

This thesis is organized into four chapters. This chapter, namely number 1, provides an introduction to the research topic and the research that is presented in this thesis. In addition, this chapter describes the organization of this thesis. Chapter 2 reviews literature and prior research performed in the area of NO_3-N leaching. The review examines the factors of NO_3-N transport through soil to subsurface drainage, and the important factors and processes for reduction of NO_3-N leaching to subsurface drainage. Further review of research

addresses the current methods of NO_3-N application and reduction in NO_3-N losses through compaction of soil and creation of flow barriers to NO_3-N leaching to subsurface drainage. Finally, the use of anion tracers and rainfall simulation as a tools in researching characteristics of NO_3-N leaching is discussed. Chapter 3 is a paper in journal article format that examines the effect of two levels of moisture content and four levels of soil bulk density in the N fertilizer application zone on leaching characteristics of NO_3-N under simulated rainfall in the laboratory. This chapter consists of an abstract, an introduction with brief review of literature, methodology, results and discussion, and conclusions. Chapter 4 provides general conclusions and recommendations of the research in this thesis. Appendix of data related to Chapter 3 follow Chapter 4. The appendix includes laboratory rainfall simulation hydrologic and chemical concentration data.

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CHAPTER 2. REVIEW OF LITERATURE

Agricultural Chemicals and Groundwater Quality.

Groundwater is an important natural resource whose quality can directly affect many people. In the U.S., groundwater is the source of about 22% of the fresh water used. About 53% of the total population and 97% of the rural population use groundwater supplies for their drinking water (Moody, 1990). Although contamination of groundwater can occur naturally, agriculture is considered one of the most widespread nonpoint sources of groundwater contamination. Chemicals of concern in groundwater quality degradation by agriculture are N and pesticides. Although salt and trace-element contamination of groundwater can be a direct result of agricultural activities, it is not due to anthropogenic chemicals. The focus here is on NO_3-N and pesticides (Bouwer, 1990).

Among all the agricultural chemicals that have the potential to contaminate groundwater, N is the most extensively used, especially by corn producers. About one million tons of N fertilizer are used annually in Iowa (Kiuchi et al., 1996). Nitrogen fertilizers are widely used in corn production in the north-central region of the U.S. N applied to cropland is of considerable importance because of the yield-increasing benefits it provides. However, cost and energy use for large quantity applications, potential NO_3-N leaching losses to subsurface water resources, and associated farmer and societal costs attached to such losses are of considerable concern, particularly in the Midwest (Hamlett et al., 1990). Because rainfall and irrigation amounts typically exceeds the annual evaporative demands in this region, drainage to groundwater or surface water (via tile drainage) can result in N movement out of the root zone (Ressler et al., 1998).

In some studies, more than 50% of the applied N was not removed by the crop or stored in the soil, and NO_3-N leaching was thought to be a major reason for these losses (Blackmer, 1987). Nitrate-nitrogen concentrations found in unsaturated soil below the root zone of agricultural fields are in the range of 5 to 100 mg L^{-1} (Bouwer, 1990). This NO_3-N eventually may enter groundwater supplies. In an Iowa study, Baker et al. (1975) found that even with modest N fertilization of corn, NO_3-N concentrations in the tile drainage often exceeded 10 mg L^{-1}. In results from a four-year study in central Iowa, Baker and Johnson (1981) reported that in 1974, drainage from plots with greater levels of applied N (250 kg ha^{-1}) had NO_3-N concentrations twice as large as drainage from plots receiving lesser applications (100 kg ha^{-1}). In 1976, concentrations were four times as large. Koplin et al. (1991) reported that 6% of 566 samples collected from 303 shallow wells in midwestern U.S. had NO_3-N concentrations that exceeded 10 mg L^{-1}.

Too much NO_3-N in drinking water can cause methemoglobinemia, or blue-baby disease, in infants. Prevention of groundwater pollution is much cheaper than restoring polluted aquifers. Using nonleaching pesticides and reducing N fertilizer applications (source control and best management practices) can result in prevention. Minimization of NO_3-N contamination of groundwater can occur by carefully controlling the timing and amount of N fertilizer applications according to crop needs (Bouwer, 1990).

Soil Hydrology

Soil Moisture Content

The conductivity equation ($Q = KA\frac{h_1 - h_2}{L}$) and physical model of this process include two important parameters determining the rate of infiltration and its temporal change.

The first is the soil water potential and the second is the coefficient of permeability. Both depend on the soil moisture content (Gusev, 1979). The soil water potential has a substantial effect on the infiltration rate in the initial stages of the process (e.g., during a rainfall event). Then its effect diminishes and eventually approaches zero. Accordingly, the infiltration rate has comparatively large values and decreases, approaching with time the value of the permeability coefficient. Hence it follows that the role of the coefficient of permeability is especially important. Gusev (1979) summarized the results of several field experiments, which indicate that the infiltration rate depends considerably on the initial soil moisture content. On the basis of setting up a series of experiments and their analysis, it was shown that during infiltration of water into soil, air becomes entrapped in its pores (Gusev, 1979). Gusev (1979) further reported that the initial moisture content is the factor determining the infiltration capacity of the soil.

Preferential Flow

Preferential flow is a general term to describe the process whereby water movement through a porous medium follows favored routes, bypassing other parts of the medium. The preferential movement of surface applied solutes and water through soil macropores is now being recognized as an important potential source of groundwater contamination (Ahuja et al., 1991). Two scales of preferential flow are recognized (Burcar et. al., 1997): (i) macropore ($\geq$ 1-mm diameter) flow, which provides rapid infiltration and transfer of water with little chance for the deeper soil matrix to influence water quality during drainage; and (ii) mesopore (<1-mm diameter) flow, which provides for lower flow velocities, allowing greater interaction at the soil-liquid interface. Under conditions of preferential matrix (mesopore) flow, a more traditional solute-soil matrix interaction should occur, thus maximizing

subsurface nutrient flux. Macropore flow, however, could allow rapid solute (nutrient) transport, bypassing the system's natural ability to remove nutrients from the infiltrating solution (Hendrickx and Dekker, 1991). However, macropores can also be a reason for reduced leaching of anions. When the soil surface is ponded with water, water quickly drains through the profile without interacting with solutes dissolved in water within aggregates, and in effect "bypassing" those solutes.

Effect of soil hydrology on solute transport

Antecedent soil moisture can also influence solute transport through a soil profile (Jardine et. al., 1990). Burcar et al. (1997) showed that higher antecedent soil moisture in the spring appears to have affected ammonium-nitrogen (NH_4-N) and NO_3-N transport through the soil profile. Under moist conditions, the greater antecedent moisture would greatly reduce micropore matric tension. By reducing the hydraulic gradient into the micropores, most flow with depth would occur through the larger mesopores as a result of gravitational potential. This would diminish surface area contact on which NH_4-N and NO_3-N retention could occur. The data thus suggest that higher soil moisture in the spring allowed NH_4-N and NO_3-N to move to greater depths before being removed from flowing solution (Burcar et. al., 1997).

Vadoze zone water and solute movement are highly complex and varied processes. Bulk flow, or piston-flow models of water redistribution based on Darcian unsaturated flow, have been extensively studied (Rose and Stern, 1965). Soil macropores, which form direct conduits for water and solute movement to greater depths and circumvent small or less conductive pores, have been described by Bouma and Anderson (1997). Schuh et al. (1997) reported that for surface applied Br and Cl tracers, and for fertilizer NO_3-N, elevated solute concentrations occurred at all depths, including the vadoze zone, the confining saturated till,

and the surface of a shallow confined aquifer, following large storms in the year of application. Detections of elevated concentrations were both temporally and spatially sporadic, and were caused by hydrologic processes that included concentrated infiltration and redistribution of water in field areas of microtopographic low elevation.

It is generally accepted that solutes such as NO_3-N and urea move readily with water in soils, and that these solutes can be leached from surface layers of soils during excessive rainfall. The leaching process has been frequently described by assuming that water entering any layer of soil displaces water already in that layer, and that solutes initially present near the soil surface are moved downward (as a "band" or as a "concentration bulge") and progressively deeper with each additional amount of water passing through the soil (Nye and Tinker, 1977). Under such conditions, the downward movement of NO_3-N would be detected by monitoring the depth of the concentration bulge. Field observations (Priebe and Blackmer, 1989) suggest that leaching could be responsible for losses of N if significant amounts of water moved preferentially through soil macropores. Preferential movement of water can result in sufficient dispersion of solutes such that a portion of solutes initially present at the soil surface moves downward distances of a meter or more before the concentration bulge moves out of the top few centimeters. This dispersion occurs when water and solutes bypass many of the smaller pores without displacing the contents of these pores.

Priebe and Blackmer (1989) reported that the shapes of N- and O-labeled water concentration profiles observed upon excavation of the columns were similar in that concentrations were greatest in the surface layers and gradually decreased with increasing depth below the surface. The distributions of labeled N found suggest that preferential

movement of water through macropores may be more the rule than the exception in Iowa soils.

Priebe and Blackmer (1989) in their study showed that recoveries of urea-derived N were greater in the dry-surface microplots than in the wet-surface microplots. There is, however, a possibility that some of the urea-derived N lost from the microplots was lost by preferential leaching through soil macropores. High moisture contents at the soil surface could be expected to promote such preferential leaching, which occurs when all the smaller pores are filled with water and additional water from rainfall bypasses most of the soil matrix by moving through macropores. The effect of initial soil moisture content deserves more attention in humid areas like the Corn Belt because farmers often apply urea to wet soil surfaces (Priebe and Blackmer 1989).

Timmons et al. (1981) summarized results of lysimeter studies throughout the U.S. Results of these studies showed that leaching of applied fertilizer N can be substantial and than NO_3-N can move rapidly in light sandy soil under intensive irrigation. Timmons et al. (1981) studied application of N under the influence of supplemental irrigation, which was necessary to produce sustained corn yields on a droughty sandy loam soil, and indicated that supplemental irrigation increased both soil water percolation and NO_3-N leaching losses. They showed that the periodic multiple application of liquid N through the irrigation system, rather than a single application in granular form, decreased average NO_3-N leaching losses by about 12 kg ha^{-1} at the 5-cm irrigation level, but no differences with method of N management were observed at the 2.5-cm level.

Fujisawa et al. (1998) showed that the release rate of N from resin-coated fertilizer was the same as the estimated value in the solution under the condition in which the soil

moisture content levels were higher than 40% (0.7 MPa of water potential) of the maximum water holding capacity. However, the release rate decreased as the level of soil moisture decreased below this point, and became nil at about 100 MPa of water potential.

Kaplunova and Aronshtein (1983) reported that accumulation of NO_3-N in the soil occurred most at a soil moisture content of 60% field capacity (FC) regardless of the form of N fertilizer applied. In this case, with consideration of the background, 76.3% of the N transforms into a NO_3-N form. An increase of soil moisture content by 15% (from 45 to 60%) led only to an insignificant increase of the amount of NO_3-N formed. Thus the dynamics of accumulation of NO_3-N depends to a considerable degree on soil moisture content and form of N fertilizer. The best conditions for the accumulation of NO_3-N are created with constant maintenance of the soil moisture content at the 60% FC level (Kaplunova and Aronshtein, 1983).

Nitrate Movement through Soil Profile and Leaching to Groundwater.

The N cycle in agricultural soils determines N availability to crops and potential N losses to the environment, such as NO_3-N leaching, NH_3 volatilization, denitrification, and in surface runoff. Nitrogen transformations in soil involve biological processes, like mineralization, immobilization, nitrification, and denitrification. Applied N not used by crops, and not lost by runoff or denitrified or volatilized, either is stored in the soil as organic-N or eventually reaches underlying groundwater (Bouwer 1990).

Groundwater movement to a waterway provides a significant component of the total flow in many Midwestern rivers and streams, and, where they exist, subsurface tile drains can transport NO_3-N from agricultural soils to these waterways (Ressler et al., 1998). Large areas of soils in the U.S. in general, and the upper Midwest in particular, are potentially

highly productive but poorly drained and, as a result, are tile-drained. Since those soils are then highly productive, they generally receive large applications of fertilizer N which can potentially be lost through the tile drains as NO_3-N. Loss of N in surface runoff is very dependent on the amount and timing of runoff. Baker and Laflen (1982) using rainfall simulation, found that about 5 and 1% of the surface-applied NH_4-N and NO_3-N, respectively, were lost with 60 mm (2.4 in) of runoff from bare plots shortly after N application. It is believed that the lower loss of NO_3-N occurred because it is very soluble and much of it moved into the soil with initially infiltrating rainwater, before runoff began (Baker and Laflen, 1983).

Bauwer (1990) noted that NO_3 is the main form of fertilizer N in soil taken up by plants. Very mobile in the underground environment, NO_3-N moves readily with deep percolation through the vadose zone to underlying groundwater. In the Midwest, NO_3-N pollution of drinking water supplies is being reported more and more frequently. Baker et al., (1975) have shown that NO_3-N in tile drainage water from row-crop land usually exceeds 10 mg L^{-1}, the MCL, with annual leaching losses averaging more than 20 kg ha^{-1}. When drainage water is not intercepted by tile drains, but instead percolates to groundwater, contamination can occur there. When drainage from the root zone is intercepted by tile drains and short-circuited back to surface waters, contamination occurs there. Nitrate-nitrogen, because of its soluble and nonadsorbed nature, will move readily with water through the soil profile.

Nutrient leaching losses are a product of concentration and volume of leaching water. Therefore, the amount of water available for leaching and the chemical concentration (rate of fertilizer N applied) at a given time are key factors influencing the leaching loss of NO_3-N.

One approach to reduce leaching of NO_3-N is to use multiple applications of N fertilizer at reduced rates (Baker and Timmons, 1984; Kanwar et al., 1988). With split N applications, the concentration of the applied N in the soil profile can be kept at a lower level than with a single, high-rate application. Baker and Timmons (1984) found that multiple applications of N using point injection resulted in greater corn yield than a single application using either deep banding or surface broadcasting of the fertilizer. Similarly, Kanwar et al. (1988) showed that a split fertilizer application with a lower total rate than the rate for the single application reduced NO_3-N concentrations in tile drainage without reducing corn yields. Several studies have been conducted to measure the loss of NO_3-N through subsurface drainage (Baker et al., 1975). Kawar et al. (1985, 1986) have summarized the results of various field experiments on the quality of subsurface drainage from croplands. These results indicate that, on the average, an equivalent of 20 to 40% of the applied N-fertilizers are being discharged to the surface water supplies through subsurface drainage waters.

Hanway and Laflen (1974) found that plant nutrient losses in tile drainage varied widely among different agricultural sites, but neither the losses nor the concentrations in the water were related to the amounts of fertilizer applied. Baker et al., (1975) further concluded that the large quantities of NO_3-N lost from some tile drains under modest fertilizer applications and the natural variation among tile drains make it impossible to assign NO_3-N losses to the use of fertilizer alone.

Gast et al. (1978) reported that application of 112 kg N ha^{-1} resulted in only slight increases in NO_3-N concentrations in the tile water or total losses from the tile lines as compared to the 20 kg ha^{-1} treatment. These results then indicate that there is relatively little increase in NO_3-N loss from tile lines or accumulation in soil profiles when N is applied at

recommended rates. Gast et al. (1978) found that graphs of NO_3-N versus. depth in the soil profile show that, with the exception of the surface 0-30 cm where NO_3-N tends to initially accumulate, there is a zone of accumulation at about 1.0 m with decreasing concentration below that depth. They concluded that N added in excess of that removed in the crop was largely lost through denitrification.

Current Methods of Fertilizer Application

Point Injector

Current methods of fertilizer incorporation, either through tillage or through subsurface knife application, require tractive energy, and in addition, bury or destroy soil-protecting surface crop residue. Losses of N through leaching or denitrification of NO_3-N can be substantial, particularly under wet conditions and when NO_3-N in excess of immediate crop needs is present in the soil. Currently, in the Corn Belt, fertilizer N usually is applied in a single preplant application as anhydrous NH_3 in the fall or in early spring, granular urea, or urea ammonium nitrate (UAN) solution. This N is susceptible to loss once the soil warms and nitrification of NH_3 to NO_3 takes place.

Baker et al. (1989) reported that losses of surface-applied fertilizers through surface runoff and volatilization of NH_3 would be reduced to near zero through soil incorporation resulting from point injection. He further noted that because of the ease of application with the rolling point-injector applicator, multiple N applications could be made to more closely match availability to crop needs and therefore potentially reduce leaching and denitrification losses.

Knife Injection

Knife injection of N fertilizer is a common application technique in the north-central region of the U.S. This technique leaves a porous knife slit in the soil above the injected fertilizer. This knife slit results in a soil zone more favorable to water movement than is the surrounding soil (Ressler et al., 1997). Ressler et al. (1998) reported that a knife applicator leaves two soil zones: (i) undisturbed soil with background N concentration and (ii) loose, porous, disturbed soil with an increased N concentration. The disturbed soil above the injected fertilizer commonly settles into the knife slit, leaving a depression that may channel nearby surface flow through the fertilizer band.

Compaction and Flow Barriers

Several management strategies have been proposed to reduce N leaching from agricultural lands. One recent strategy is to divert the flow of infiltrating water away from or around the N fertilizer. Such an approach was taken by Baker et al. (1997) as one way to alter water flow in soil by compacting the soil above applied fertilizer. Compacted soil can be used as a barrier to water flow, limiting water and chemical movement in the fertilizer band. Also, chemical incorporation associated with tillage can result in reduced leaching compared with no-till because macropores are disrupted and there is less bypass water flow (Kanwar et al., 1985).

Baker et al. (1997) reported that after addition of potassium bromide (KBr) solution to a soil column that received a point injector with compaction (CPI), the soil in a 10-cm diameter area around the hole was compacted by dropping a 4 kg, 24-mm diameter metal rod 100 times from a height of 10 cm. This method was chosen to provide a repeatable laboratory procedure for applying the compaction part of the CPI treatment. The resultant depressions

were refilled with extra topsoil taken from the plots. In the field, depressions of this size probably would require a load of 2000 to 4000 Newton.

Ressler et al. (1998) reported that results from several recent studies show that the orientation and physical condition of surface soil layers play a role in chemical transport through the soil. Ressler et al. (1998) discuss that ridge tillage, a management practice developed to influence water and heat storage in row crops, was previously investigated as means to also reduce NO_3-N leaching. Clay et al. (1992) and Hamlett et al. (1990) demonstrated that N injected into an elevated ridge was less susceptible to leaching compared with N injected into furrows between ridges or N injected into a level soil surface. Baker et al. (1997) and Kiuchi et al. (1994, 1996) have shown that compacted soil could be used above injected chemicals to divert water around the chemicals and reduce their leaching.

A layer of compact soil immediately below the depth of plowing called a plow sole, and traffic soles are commonly observed in cultivated soils (Baver et al., 1972). Tillage implements tend to produce localized compaction with the friction at the soil-metal interface (Nicholas et al., 1958). Reaves and Cooper (1960) reported that maximum compaction produced by track-type tractors occurred at about the 8-cm depth. Hira et al. (1979) discussed that the density and thickness of a compact zone depends upon the type of implement and traffic, nature of the soil, crop management, water content of the affected layer, and duration for which the compressive force works. Hira et al. (1979) reported that soil columns were compacted to bulk densities of 1.62 g cm^{-3} and 1.80 g cm^{-3}. The presence of a compact zone in the soil columns affected the distribution of water and Cl from a surface-applied calcium chloride ($CaCl_2$) slug. The peak Cl concentration was higher in layered soil columns as

compared with unlayered columns (Hira et al., 1979). The Cl distribution and displacement of the peak Cl concentration appear to result from variation in molecular diffusion and hydrodynamic dispersion effects in layered and unlayered soil columns (Hira et al., 1979). A compact zone with smaller pores sandwiched between soils with larger pore size would cause the water to move under greater unsaturation even when the surface soil is saturated (Gumbs and Warkentin, 1972). Thus, pore combination below the compact zone which carries water in the layered columns may vary from medium to small sizes, but in the unlayered columns, the pores conducting water may range from large to small in size (Hira et al., 1979). The variation in the pore water velocity is reduced in the former case. As a result of this, longitudinal hydrodynamic dispersion of the salt slug is reduced (Hira et al., 1979). Further, as the solution passes through soil pores, anion exclusion limits the presence of Cl in relatively immobile water adjacent to a more mobile zone of downward moving water stream (Van Schaik and Kemper, 1966). Within the compact zone, a proportion of water, which is relatively immobile and free from Cl due to anion exclusion effects, becomes greater (Hira et al., 1979). Consequently, Cl is increasingly concentrated within smaller quantities of the relatively mobile water, and thus leads to greater leaching of soluble salts (Hira et al., 1979).

Improved Management Practices

To help minimize NO_3-N losses from agricultural lands, improved management practices need to be adopted. A modified surface configuration combined with fertilizer N placement away from zones of substantial vertical water movement should help to minimize NO_3-N leaching (Hamlett et al., 1990). Hamlett et al. (1990) reported that one such configuration is the ridge-tillage system in which elevated ridges are constructed by forming inverted v-shaped mounds of soil. He further noted that N fertilizer can be placed in the

elevated portion of the ridge. Runoff from the ridges will concentrate in the valleys, below and away from the area of greatest N concentration. With this configuration, the potential for NO_3-N leaching should be less than with traditional, flat tillage systems (Hamlett et al., 1990).

Hamlett et al. (1990) investigated the water movement and NO_3-N and Br concentrations within the upper 1.2 m of the soil for ridge and flat tillage configurations. With fertilizer solution placed in the ridge row, NO_3-N leaching was less likely because more water moved though the ridge midrow zone instead of the ridge row. For a 50-mm rain, while less water was stored from the flat plot (81% recovery) than from the ridge plot (95% recovery), more water was stored in the untracked ridge row and flat row zones than in the tracked ridge midrow and flat midrow (Hamlett et al., 1990). Comparison of ridge row and ridge midrow profiles provided further evidence that runoff moved from the ridge row to the ridge midrow and then downward into the soil. Comparing ridge row and flat row profiles illustrated that less NO_3-N moved downward in the ridge plot in contrast to the flat plot (Hamlett et al., 1990). These data suggest that the ridge helps to isolate NO_3-N from leaching even when equal downward water movement occurs. The ridge configuration concentrated more runoff in the midrows, therefore, more water infiltrated below and away from the fertilized zone.

Kiuchi et al. (1996) explored an approach to reducing anion leaching through the use of a subsurface water-flow barrier. Studies have indicated, in theory, that the presence of a localized, impermeable subsurface barrier should direct infiltrating water away from the barrier and reduce the flow rate in the vicinity of the barrier (Kiuchi et al., 1996). Thus, it is conceivable that NO_3-N leaching could be reduced if the fertilizer is placed in a "low-flow"

region just above or below a barrier. One way to alter water flow in soil is to compact the soil. Soil compaction destroys the large voids and channels that may readily conduct rainwater in the upper soil profile. The reduced porosity of compacted soil makes it difficult for water to infiltrate (Ankeny et al., 1990). If compaction occurs in localized zones, much of the infiltrating water is directed away from the compacted soil zone and toward more permeable, uncompacted soil. Further, water flow just above and below the compacted soil layer should be reduced. It is, therefore, conceivable that a compacted soil zone will serve as a water flow barrier. NO_3-N placed just below a compacted zone of soil is less likely to be immediately carried down by the infiltrating water (Kiuchi et al., 1996).

The same principle might be applied to conventional fertilizer banding with a knife applicator. During normal operation, knife applicators create a furrow partly filled with loose soil directly above the fertilizer band. Undoubtedly, the soil above the fertilizer band is very permeable and provides pathways for preferential water flow directly through the band. Therefore filling in the knife furrow and compacting the soil above the fertilizer band may redirect some of the water flow away from the applied fertilizer.

Kiuchi et al. (1996) reported that localized compaction zones need not be detrimental to crop growth. First, only small volume of soil needs to be compacted. Secondly, plant roots are capable of compensating for the reduction of growth caused by unfavorable conditions, such as soil compaction, in part of the root zone by proliferating in more favorable soil zones (Willis et al., 1963 and Kasper et al., 1991). Thus, it is expected that corn roots can encounter banded fertilizer by growing around a compacted soil zone.

Kiuchi et al. (1996) examined the effect of subsurface water-flow barriers on leaching losses of NO_3-N and Cl with no subsurface barrier (NB), a polyethylene sheet placed above

the chemical band (PA), a polyethylene sheet placed below the chemical band (PB), a compacted soil layer formed in situ above the chemical band (CL), and the check (CK), with no subsurface barrier or application of Cl and NO_3-N. Kiuchi et al. (1996) reported that leaching loss of Cl was significantly reduced when subsurface flow barriers were used. Among the three barriers tested, a plastic sheet placed above the band (PA) was the most effective subsurface barrier and a compacted soil layer above the band (CL) was the least effective in reducing leaching loss of Cl. However, all three subsurface flow barrier treatments significantly reduced leaching loss of Cl compared with NB. Cumulative leaching loss of NO_3-N after 350 mm of drainage was significantly reduced when subsurface barriers were used Kiuchi et al. (1996).

Localized Compaction and Doming (LCD)

Surface ridges, compacted soil layers, and macropore disruption are strategies that can reduce leaching. Ressler et al. (1997) described an N fertilizer applicator involving localized compaction and doming (LCD) that attempts to combine these strategies to smear and close macropores below the N-injection knife, fill and compact soil into the knife slit, and cover the fertilizer band with a surface ridge or dome.

In a practical way, the route of water movement relative to the location of an anion like NO_3-N might be altered through localized compaction at the point of anion application. This could be accomplished by modification of the point-injector fertilizer applicator (Baker et al., 1989). For example, Baker et al. (1997) suggested that a second wheel with "feet" could be added and synchronized to follow the point-injector wheel.

An N fertilizer injector has been designed and built that forms a locally compacted soil layer and a surface ridge or dome, LCD, over the injected fertilizer band (Ressler et al.,

1997). The injector includes a knife with a triangular, horizontal shoe at the base that smears the soil at the bottom of the knife slit to close any existing macropores. A cone disk guide wheel follows the knife, to close the knife slit and compress a soil layer over the fertilizer band. Another following wheel completes the closure of the slit and mounds soil over the fertilizer band. These soil manipulations are performed in between crop rows at the time of fertilizer injection, and no additional soil management was conducted during the growing season (Ressler et al., 1998). Reesler et al. (1997) described that physical properties of the soil within the dome and subsurface barrier indicated that the soil manipulations with the LCD injector reduced water flow through the injected fertilizer band compared with the conventional knife injector. Measurement of soil bulk density, water infiltration, and soil penetration resistance around both conventional knife-injected and LCD-injected fertilizer bands indicate that the probable water flow path would be diverted around the LCD fertilizer band rather than through it, as is the case with the conventional knife fertilizer band. Ressler et al. (1997) compared such properties of soil and showed that the conventional knife slit was filled with loose soil that had low bulk density. The bulk density measured in the knife slit was 1.2 g cm^{-3}; whereas, the average bulk density of the undisturbed soil surrounding the knife slit was 1.4 to 1.5 g cm^{-3}. The loose soil in the knife slit had a porosity of 0.53, compared with the porosity of 0.44 for undisturbed soil. The compacted soil layer generated by the LCD applicator was a diagonally oriented soil wedge of bulk density 1.4 g cm^{-3}.

Ressler et al. (1997) in his study reported that the ponded infiltration rate after 30 min for soil above a conventional knife band was 19.7 cm h^{-1}. In contrast, the infiltration rate for soil above an LCD band was 10.1 cm h^{-1}, a statistically significant reduction in surface

infiltration. The reduced infiltration rate was caused by the smaller porosity and thus the increased hydraulic resistance of the compacted layer.

Ressler et al. (1998) showed that LCD-injected anions (2,6-difluorobenzoic acid, pentafluorobenzoic acid, and o-(trifluoro-methyl) benzoic acid) were less susceptible to leaching to subsurface drains in lysimeters than conventional knife-injected or broadcast anions. Ressler et al. (1998) noted that the pattern of solute redistribution in the knife plot suggests that transport was dominated by downward movement with water (i.e., advective transport or mass flow). The LCD plot instead showed a more diffusive redistribution, which suggests water flow through the injected chemicals was reduced compared with the conventional knife treatment. Surface layer masses of NO_3-N and Br were greater for the LCD plots than those of conventional knife plots. This suggests that, during a year when precipitation is abundant, the LCD method limits movement of N out of the injection zone near the soil surface, and thus reduces leaching. Localized compaction around the point of anion application significantly reduced anion leaching in undisturbed columns of soil compared with surface-broadcast or undisturbed point-injector applications (Baker et al., 1997).

The conventional knife profile showed that the NO_3-N center of mass moved to below 30 cm, and the maximum concentration was 59 mg kg^{-1}. In contrast, the center of mass in the LCD profile was approximately 20 cm deep, and the maximum concentration was 128 mg kg^{-1}. The lower edge of the NO_3-N mass applied by the LCD applicator (20 mg kg^{-1}) moved only 60% as deep as NO_3-N applied by conventional knife applicator (Ressler et al., 1997).

Tracer Anions

Schuh et al. (1997) used three tracers to evaluate the movement of water and solutes from the soil surface to the Carrington aquifer. Applied tracers included Br (87 kg Br ha^{-1} as KBr) and Cl (380 kg Cl ha^{-1} as KCl). Bromide and Cl are highly water soluble and have minimal adsorption and precipitation tendencies under normal field conditions.

Ressler et al. (1998) performed leaching and yield investigations on Nicollet slit loam. Injection treatments were (i) injection of liquid solution containing calcium nitrate ($CaNO_3$) and KBr using a conventional knife injector and (ii) injection of the same liquid solution using the LCD injector (Ressler et al., 1997). Calcium nitrate fertilizer solution was applied to maintain constant and reproducible NO_3-N injection rates for the plots. Additionally, the solution contained Br as tracer of NO_3-N movement. Bromide moves similarly to NO_3-N in this soil, but is not subject to the microbial processes and gaseous losses that may affect soil NO_3-N concentrations (Kessavalou et al., 1996). Because Br is not native to these soils, distributions determined during soil sampling gave a clear representation of soluble chemical movement in the soil (Ressler et al., 1998).

Rainfall Simulation

Meyer et al. (1979) reported that soil erosion data can be obtained more rapidly and efficiently by using simulated rainfall rather than relying on natural rainfall. To evaluate row sideslope erosion, runoff, and sediment-size distributions for various typical field conditions, a new rainfall simulator was designed and constructed. Design characteristics included: 1. a wide range of intensities that are typical of erosive rainstorms; 2. drop size, velocity, and impact energy characteristics similar to those of natural rainstorms; 3. capabilities to apply simulated rainfall uniformly to a short length of cropped row or other small interrill area; and 4. minimum time between simulated raindrop applications, if intermittent.

Meyer et al. (1979) described that the spray nozzle oscillates in an arc of about 90^0, but a clutch-brake was added to delay the nozzle after each pass across the research plot. Delay time is varied by an electronic timer to give a wide range of application intensities. Although this causes an intermittent application of spray, intermittent spray is used on many rainfall simulators because it is the best compromise for attaining the necessary larger drops, greater impact velocities, and reasonable intensities.

Meyer et al. (1979) further reported that two Veejet nozzles (spraying systems company) are mounted side-by-side so that either can be used for rainfall application. The impact velocities of different drop sizes for a 3-m (10-ft) fall and a nozzle pressure of 41 N m^{-2} (6 psi) were used. Each pass of the nozzle across the plot takes just less than 0.5 s. The duration of the delay after each pass determines the rain intensity, and the timer that controls this duration can be set for delays from 0 to 10 s by 0.1-s intervals. Tests using this equipment have shown that it can provide useful data on row–sideslope erosion, runoff rates, and sediment size distributions (Meyer et al., 1979).

Baker et al. (1997) performed rainfall simulation with soil columns to study localized compaction and doming to reduce leaching of injected anions. Rainfall was simulated by using three rows (70 cm apart) of oscillating nozzles, 107 cm in a row, operating at a pressure of 6.2 N cm^{-2} (Meyer and Harmon, 1979). Rainfall intensity was controlled by the time delay between sweeps over the column. All soil columns were positioned in exactly the same location, 3 m under the simulator, with the edges of columns at 45^0 to the direction of the nozzle sweep (Baker et al., 1997).

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CHAPTER 3. USING RAINFALL SIMULATION AND TRACER ANIONS TO STUDY THE EFFECTS OF SOIL BULK DENSITY AND SOIL MOISTURE ON NITRATE LEACHING CHARACTERISTICS.

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Abstract

Potential NO_3-N leaching losses with subsurface drainage are of considerable concern, particularly in the Midwest. The overall purpose of this research was to study the effects of soil bulk density in the zone of N application and initial soil moisture on NO_3-N leaching from surface soil during the laboratory rainfall simulation with the help of tracer anions. Simulated rainfall was applied at an intensity of 6.5 cm h^{-1} for 70 min to soil pans with compacted soil bars, containing additional NO_3-N, of 1.10, 1.33, 1.57, and 1.81 g cm^{-3} bulk density and initial soil moisture contents of 10 and 15% by mass. Surface runoff, subsurface drainage, and soil and sand extract samples were analyzed for NO_3-N, Br, and Cl concentrations. Surface runoff losses of NO_3-N and Br were greater at 15% moisture content because of greater runoff volumes. Higher bulk density in the zone of N application caused lower concentrations and losses of NO_3-N in the subsurface drainage, resulting in a significant difference between bulk densities. The 15% moisture content produced less NO_3-N leaching losses because subsurface drainage began later and had a lesser volume. Nitrate-nitrogen mass balance indicated that higher bulk density and moisture content resulted in retention of greater amounts of NO_3-N in soil. Bromide concentrations and losses and Cl losses in subsurface drainage were lower at 15% moisture content.

Introduction

The use of inorganic fertilizers, particularly N, has been recognized for much of the increase in corn yields in recent years. Baker et al. (1989) reported that in the U.S., yields increased from below 1.9 t ha^{-1} in the 1930s to more than 6.9 t ha^{-1} in 1980. They also reported that in the same period, annual total fertilizer use of all crops increased from less than 2 million to more than 20 million t. Between 1960 and 1980, total plant nutrient use in the U.S. increased on average 5.8% per year. Nationwide, the average growth rate for N of 7.4% per year has been the highest of the three primary plant nutrients, N, phosphorus (P) and potassium (K). Baker et al. (1989) found that leaching occurs when the mobile NO_3 ion moves through the soil profile with excess water. Baker et al. (1975) found that an average of 31 kg ha^{-1} (28 lb ac^{-1}) per year of NO_3-N was lost with 150 mm (5.9 in) of subsurface drainage water, with a maximum of 93 kg ha^{-1} (83 lb ac^{-1}) lost in one year with 360 mm (14.2 in) of flow from an individual subsurface drain.

Subsurface fertilizer banding using a conventional knife applicator is one of the most common methods for N fertilization of corn in the North Central Region of the U.S. A knife is pulled through the soil to open a furrow into which a fertilizer can be injected. Anhydrous ammonia (NH_3) is the most widely used N source in this type of application. Knifing incorporates the N fertilizer so that volatilization losses of NH_3 can be limited. However, N fertilizer losses by NO_3-N leaching from the root zone are as troubling as losses to volatilization, because of the environmental and health risks associated with NO_3 contamination of water resources.

Several management strategies have been proposed to reduce N leaching from agricultural lands. One recent strategy is to divert the flow of infiltrating water away from or

around the N fertilizer. Such an approach was taken by Baker et al. (1997) as one way to alter water flow in soil by compacting the soil above applied fertilizer. Compacted soil can be used as a barrier to water flow, limiting water and chemical movement in the fertilizer band. Ressler et al. (1997) illustrated that the LCD-injected (Localized Compaction and Doming) chemicals showed significantly less leaching compared with the conventional knife-injected chemicals. Ressler et al. (1998) reported that results from several recent studies show that the orientation and physical condition of surface soil layers play a role in chemical transport through the soil. Ressler et al. (1998) showed that the mass fraction leached was reduced by diverting water around an injected chemical band by closing macropores at the bottom of the knife slit, and by closing the knife slit with a compacted soil layer and a surface dome.

Nitrogen fertilizer must remain in the rootzone to be taken up by plants. Thus, a means of reducing the percolating water flow rate or diverting percolating water away from applied N fertilizer should help maintain fertilizer N in the rootzone for an extended period. A localized, impermeable subsurface barrier will divert infiltrating water away from the barrier. Low-flow regions should occur within and just above and below the centerpoint of the barrier. Leaching of NO_3-N may be reduced if fertilizer is placed in that low-flow region. In effect, compacted soil may act like a subsurface flow barrier and water flow may be directed away from the applied fertilizer.

The overall purpose of this research was to study the effects of bulk density in the zone of N application and soil moisture on NO_3-N leaching from surface soil during the laboratory rainfall simulation with the help of tracer anions. Specifically, simulated rainfall with Br dissolved in it was applied to soil in pans of two different initial soil moisture contents and that had been treated with NO_3-N and Cl, with the following objectives:

1. To study the impacts of two levels of soil moisture and four levels of bulk density in the zone of N application on the leaching characteristics of NO_3-N.
2. To use this information to help in the development/improvement of N application methods/equipment.

Materials and Methods

The study reported here was conducted in the Porous Media Laboratory in the Agricultural and Biosystems Engineering Department on the Iowa State University campus. Simulated rainfall was applied to soil runoff pans to evaluate the effectiveness of using tracer anions to study the fate and transport of solutes in surface runoff and subsurface drainage, and to determine the impact of soil moisture content and bulk density in the zone of N application on the transport of NO_3-N. The determination of volumes of surface runoff, subsurface drainage, and water storage in the soil were part of the analysis. Two levels of initial soil moisture content (10 and 15%) and four levels of bulk density (1.10, 1.33, 1.57, and 1.81 g cm^{-3}) were tested in a factorial experiment for a total of eight treatments, with three replications per treatment. The treatments are denoted as 10% moisture, 1.10 g cm^{-3} bulk density (10-1.10); 10% moisture, 1.33 g cm^{-3} bulk density (10-1.33); 10% moisture, 1.57 g cm^{-3} bulk density (10-1.57); 10% moisture, 1.81 g cm^{-3} bulk density (10-1.81); 15% moisture, 1.10 g cm^{-3} bulk density (15-1.10); 15% moisture, 1.33 g cm^{-3} bulk density (15-1.33); 15% moisture, 1.57 g cm^{-3} bulk density (15-1.57); 15% moisture, 1.81 g cm^{-3} bulk density (15-1.81).

Soil

The soil used for this study was obtained from Iowa State University research center near Ames. The soil was mapped as Nicollet loam (42% sand, 52% silt, and 6% clay) with 1

to 3% slope, and somewhat poorly drained on slightly convex or plane slopes on knolls and swales. The soil was taken from the top 25 cm of a field in a corn-soybean rotation. Prior to use in rainfall simulation, the soil was sieved on 5- and 2- mm screens to separate residue and to remove large soil aggregates, then mixed in a portable, rotating drum concrete mixer to establish homogeneity. The sieved soil was analyzed for the background levels of NO_3-N, Cl, Br, and moisture content. The 10 or 15% soil moisture, by weight, was created by adding distilled water with Cl-tracer in it to the soil through a pressurized spray nozzle while mixing the soil in the rotating concrete mixer drum. After addition of water, the soil was thoroughly mixed for 30 min and then was transferred to plastic bags and stored in containers located indoors for at least 3 days before being used.

Runoff Pans

Plastic lids of large storage containers were used as runoff pans. The dimensions of plastic pans were 81.2 cm long by 42.2 cm wide, resulting in 3396 cm^2 rainfall collection surface area. The dimensions of the soil surface area were slightly less (because of a small shoulder in the pan needed for strength) at 80.5 cm long by 41.0 cm wide resulting in a 3281 cm^2 surface area (Figure 3-1). A 0.95-cm inside diameter perforated polyethylene drain tube was inserted into the bottom of each pan to serve as a subsurface drain. Fine silica sand was placed in the bottom of each pan over the drain tube to a depth of 3.8 cm; and above the sand, a predetermined mass of soil (27.4 kg dry weight) was compacted in three successive layers to a 7.6 cm thickness, resulting in a dry bulk density of 1.1 g cm^{-3}. The second layer was divided into two sublayers, and a compacted soil bar with line source of NO_3-N in it was placed in two parts in line between those sublayers. Since the length of the u-shaped channel used to prepare the compacted bar was only half of that of runoff pan, the bar consisted of

two parts placed end-to-end in the runoff pan. Sheets of cheesecloth and fiberglass screen were placed between the sand and soil layers to keep them apart and to allow for separation later. Twelve-cm tall plexiglas sideboards were attached at the rim of each pan to reduce water and sediment loss due to raindrop splash. Prior to simulation, each pan was tilted at 4% slope. The runoff pans were positioned a 3.05 m below the rainfall simulator.

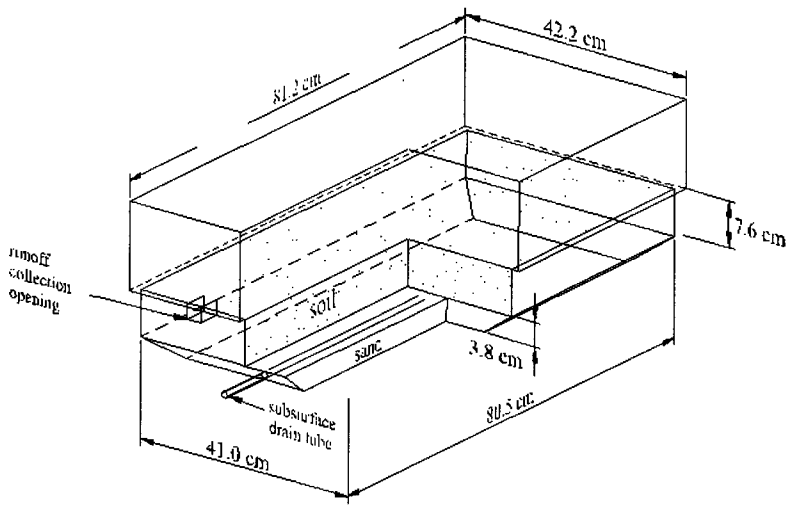

Figure 3-1.Schematic diagram of soil pan.

Compacted Soil Bars

Aluminum channels were used as "forms" to hold the soil in a rectangular cross-section as it was being compressed to create compacted soil bars. The dimensions of aluminum channel were 38.100 cm long by 2.667 cm wide by 2.286 cm high, resulting in 101.61 cm^2 surface area and 232.29 cm^3 volume. Each aluminum channel was packed with 255.5 g (dry weight) of soil, with 19 mL of $Ca(NO_3)_2$ added to it, which gave an initial bulk density of 1.1g cm^{-3}. A "Sintech" computer-integrated testing machine by MTC Corporation

was used to compress the soil bars to the desired bulk densities (see Figure 3-2). The computer-controlled system allowed good repeatability. Compression was done by using a 5-Newton grid cell and iron press bar attached to it with dimensions fitting inside the aluminum channel. The entire process of compaction was controlled by using computer software integrated with the machine. The key factor in compression was the distance of travel/depth of compression, which determined the final soil bulk density. Software was used to input values for the speed of movement of the press bar attached to a grid cell and the time of travel. By fixing the speed and varying time of travel, the desired distance of travel was reached, which was related to bulk density. Travel speed was set at 0.0254 cm min^{-1} (0.01 in min^{-1}) and time of travel was set to be the stop point for compression. For example, the 1.81 g cm^{-3} bulk density required a final soil volume of 141.17 cm^3 (V=255.5/1.81) and soil depth of 1.39 cm (d=V/A=141.17/101.61). Thus, the distance of travel of the compression grid cell from the start at the original soil surface was 0.8967 cm (2.286-1.389), requiring 35.31 min. The plastic wrap was placed inside the aluminum channel to create less friction between soil and aluminum channel for easier removal of soil after compaction. After compression to the desired density was complete, the compacted soil bars were allowed to set at room temperature for one day before they were removed from the aluminum channels. This allowed the soil bars to partially dry and made possible their removal from the aluminum channels without breaking them.

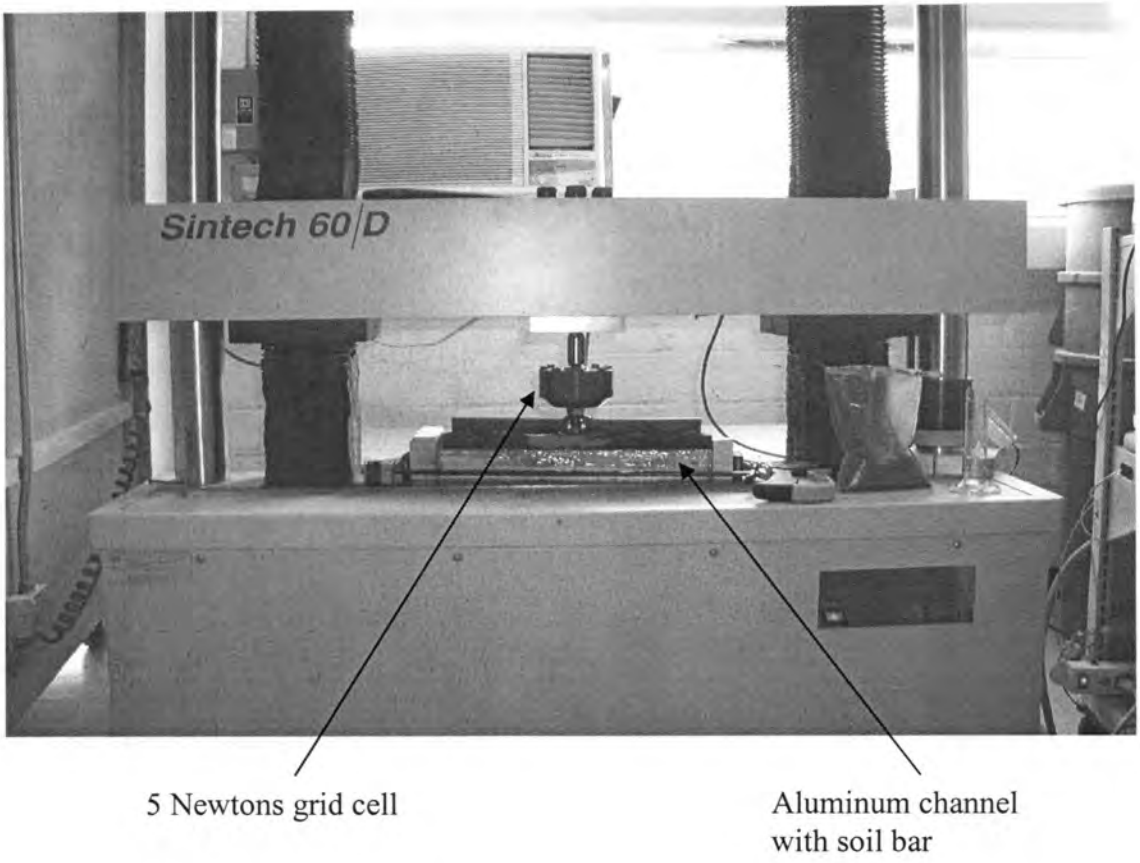

Figure 3-2. Picture of compressing apparatus.

Nitrate Application and Tracer anions

Two tracer anions, Cl and Br were used to evaluate the movement of water and solutes from and through the soil to surface runoff and subsurface drainage. Chloride was added to soil (an equivalent to 112 kg ha^{-1} for the area of the layer of soil 7.6 cm deep at a bulk density of 1.1 g cm^{-3}) in water solution and the soil was stored for at least three days indoors. Bromide was added to rainwater (at 50 mg L^{-1}) and rained upon the soil pans. Nitrate-nitrogen (112 kg ha^{-1} as $Ca(NO_3)_2$) was added to the soil that was compacted into the soil bars. Each soil bar received 19 mL of NO_3-N solution treatment prior compaction, with

two compacted bars placed end-to-end in each soil pan (two bars were used, instead of one, for reason of ease of preparation and handling).

Procedure

Two runoff pans were used simultaneously during each rainfall simulation run. Rainfall was applied to the pans at the rate of 6.5 cm h^{-1}. Before and after rainfall simulation, soil and sand samples were taken for determination of initial and final moisture contents; the total weight of the soil-water-pan system was also taken before and after simulation to cross-check water storage calculations. An indoor rainfall simulator with 12 spray nozzles located overhead in three lines was used to produce simulated rainfall. The simulator was positioned 3.05 m (10 ft) above the runoff pans (See Figure 3-3). The combination of nozzle height, operating pressure of 6.9 N m^{-2} (10 psi) at the point of measure (41 N m^{-2} (6 psi) at the nozzle), and flow rate created droplet sizes and velocities similar to natural rainfall. An electronic timer that controlled the sweep period of the nozzle could be adjusted to attain the desired rainfall intensity.

The intensity and volume of rainfall were measured with an aluminum channel rainfall collector, 101.5 cm long by 3.2 cm wide, placed between the two pans, and with six 2.5 cm diameter rain gages placed around pans. Rainfall and runoff from the two pans were individually routed through transfer tubes to sample containers on electronic balances (see Figure 3-3). Pan surface runoff samples were collected at 2-min intervals after the start of runoff and subsurface drainage samples were taken at 4-min intervals after the start of drainage. The subsurface drain tube was left open until the start of rainfall, when a small vacuum pressure of 12 cm of water was applied to each subsurface drain tube by an electric vacuum pump to expedite sampling of subsurface drainage water.

After the rainfall simulation was completed, soil and sand from the pans were separated, sampled for moisture content, and transferred to large plastic containers for anion extraction and analysis. Extractions were performed using a 2:1 ratio by weight of distilled water to soil/sand. Soil/sand and water were thoroughly mixed with a heavy duty electrical drill and stirring rod twice for 5 to10 min intervals prior to extract sampling.

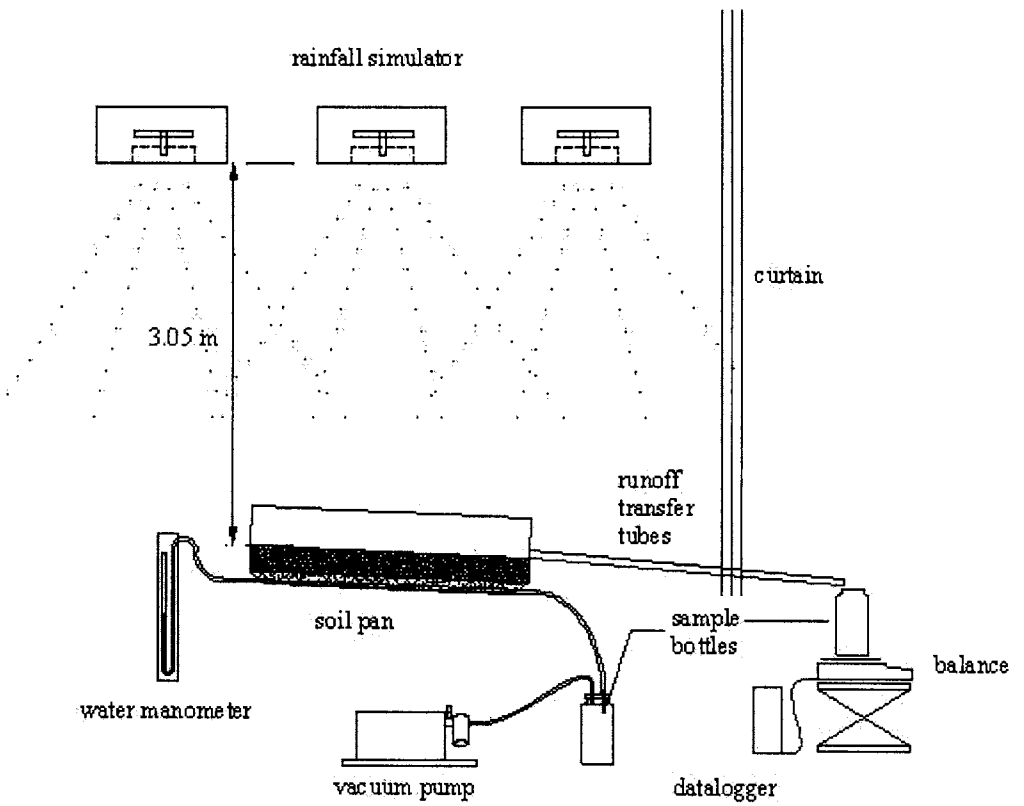

Figure 3-3. Rainfall simulator, surface runoff, and subsurface drainage collection apparatus.

Analysis

Pan surface runoff samples collected every 2 min and weighed, were then composited into samples for chemical analysis. The first two samples were used to make up the first composite sample, and every four samples after that were used to make up the rest of the

composite samples. Subsurface drainage samples, collected every 4 min, were retained as individual samples. Water samples were analyzed for NO_3-N, Br, and Cl concentrations.

Nitrate-nitrogen was analyzed by the automated flow injection cadmium reduction method using a Lachat Quickchem 2000 Automated Ion Analyzer system. In this method, NO_3-N is reduced to nitrite (NO_2) by a cadmium/copper column. Nitrite is diazotized with sulfanilamide and then reacted with N-(1-naphthyl-)-ethylenediamine dihydrochloride at a pH of 8.5 to form a colored (pink to red) azo compound, whose intensity is proportional to the amount of NO_3-N plus NO_2-N in the sample. Measurements were made with a colorimeter at a wavelength of 520 nm, and NO_3-N + NO_2-N concentrations in samples were determined by comparing sample absorbance with those obtained from a calibration curve comprised of standards containing NO_3-N concentrations from 0.25 to 30.0 mg NO_3-N L^{-1}.

Cl analyses were performed by the automated flow injection ferricyanide method using the same Lachat 2000 Automated Ion Analyzer system. Chloride forms a soluble complex with mercuric thiocyanate. The freed thiocyanate ion reacts with iron(III) to form a red-orange colored compound whose intensity is proportional to the concentration of the Cl in the sample. Measurements were made with a colorimeter at a wavelength of 480 nm. Chloride concentrations in samples were determined by comparing sample absorbance with those obtained from a calibration curve comprised of standards containing Cl concentrations from 1.00 to 100 mg Cl L^{-1}.

Bromide analyses were performed by the automated flow injection phenol red method using the same Lachat 2000 Automated Ion Analyzer system. Chloramine-T reagent oxidizes bromide to bromine which is then brominated with phenol red (buffered at pH of 4.5-4.7) to form a reddish to brown colored compound whose intensity is proportional to the

concentration of Br in the sample. Measurements were made with a colorimeter at 590 nm. Bromide concentrations in the sample were determined by comparing absorbance of the sample with a calibration curve based on absorbances of standards containing Br concentrations from 1 to 60 mg Br L^{-1}.

A complete randomized block design was used with three blocks and 24 experimental units (EU), each block being four bulk densities and two moisture contents, and an EU being a pan of soil. A 2x4 factorial was used and analysis of variance (ANOVA) was performed using two tests: student's t-test and least significant difference test (LSD). The Statistical Analysis System (SAS) was used for developing relationships between moisture content of soil and bulk density and NO_3-N in subsurface drainage.

Results and Discussion

Water Mass Balance

Rainfall simulations of 6.50 cm h^{-1} (2.55 in h^{-1}) intensity were applied to all pans for the duration of 70 min, resulting in 7.58 cm of rain. The mean rates of surface runoff and subsurface drainage averaged over replications versus time are shown in Figures 1 through 8 for the eight treatment combinations. The mean rates of runoff and subsurface drainage for 10 and 15% moisture contents averaged over replications and bulk density treatments (density of the NO_3-N treated soil bars did not have an effect on the overall hydrology) are shown in Figure 9. The cumulative infiltration for 10 and 15% moisture contents averaged over replications and density treatments are shown in Figure 10. The impact of the soil moisture content and bulk density on hydrology and water mass balance is given in Tables 1, 2, and 4. Effect of moisture content on water storage in the soil and sand, as well as final

moisture contents of soil and sand are shown in Table 3. Infiltration analyses for moisture content effects are shown in Table 5.

Surface Runoff

The moisture content effect was significant ($P<0.0001$) for surface runoff start times and runoff volumes. Surface runoff began sooner for treatments with 15% moisture than for those with 10%. The time-to-runoff for treatments with 15% moisture on average was 11.3 min while for treatments with 10% moisture it was 21.8 min. The 15% soil moisture content resulted in greater volumes of runoff than 10% soil moisture content, with average volumes of 5.1 and 3.3 cm, respectively. It is possible that the rainfall energy falling on the soil with the higher initial soil moisture increased sealing off of the soil surface during rainfall and decreased water infiltration into the soil, resulting in more runoff (and also in less subsurface drainage). The trend of accumulated infiltration with time can be seen in Figure 10. Because the compacted soil bars represented only 3% of the soil surface area and only 0.9% of the soil volume for the 1.1 g cm^{-3} density (even less for the other bulk densities), the effect of bulk density treatment did not have a significant effect on surface runoff start times and volumes.

Subsurface Drainage

The effect of soil moisture content was significant ($P<0.0001$) for subsurface drainage start times and volumes. Higher subsurface drainage rates and earlier drainage start times produced significantly more subsurface drainage volumes from the 10% moisture treatments than from the 15% moisture treatments. The 10% soil moisture treatment produced 1.7 cm of subsurface drainage on average, while 15% soil moisture produced 0.6 cm. Average times-to-drainage for the 10 and 15% moisture contents were 28.7 and 43.7 min, respectively. Timing and volume of subsurface drainage was unexpectedly faster and greater, respectively,

for soils with the 10% moisture content treatment. The effect of bulk density treatment on subsurface drainage start times and volumes did not have a significant effect due to fact that the compacted soil bar represented very small percentages of the soil surface area and soil volume in the pan, as discussed in the previous section.

Storage

The effect of initial soil moisture content was significant on water storage in the soil. As expected, more rainwater was stored in the soil for treatments with 10% moisture content than those with 15%, with an average of 2.32 and 1.55 cm stored, respectively. Furthermore, initial soil moisture content had significant effect on final soil moisture contents, with average values of 37.4 and 33.5% for 10 and 15% initial moisture contents, respectively. Greater storage for the 10% moisture content can possibly be explained by greater water holding capacity of the soil and more rapid infiltration rates (see Figure 10). Hydrological analyses in Table 5 indicate that time to wet the soil from 10 to 15% moisture should have only taken 3.9 min. Based on the information from time-to-runoff for 15% moisture, predicted time to runoff for 10% moisture was 15.2 min. However, the time-to-runoff was 6.6 min later. Furthermore, time-to-subsurface drainage for 10% moisture content was 19 min early. In theory, final moisture contents would have been expected to be the same for both 10 and 15% initial moisture contents, with the difference of 5% in initial moisture content equal to 0.40 cm of water. However, the difference between 10 and 15% moisture treatments was 0.77 cm of water storage, which is greater than 5%. One possible reason for such a difference may be due to differences in packing and soil aggregate sizes (and possibly trapped air) of the soil at different initial moisture contents.

Measured values of final soil moisture content were compared to moisture content data obtained by professor Jian Zhou using Time Domain Reflectometry (TDR). They showed that the effect of initial soil moisture content was significant on final soil moisture contents. They also showed similar differences in final soil moisture contents. The correlations for measured final soil moisture content and that measured by TDR were statistically significant (P=0.035) for 10% initial moisture content treatment. However, probably due to narrow ranges in moisture contents for 15% initial moisture treatment, the correlations were not significant. Not surprisingly, initial soil moisture content did not have a significant effect on water storage in sand.

Recovery

Average rainfall recoveries of the intended 7.58 cm for 10 and 15% moisture were 7.97 and 7.93 cm, respectively, resulting in very good percent recovery as shown in Table 2. Negative differences in Table 2 indicate some rainwater missing from the system. The most logical source of error in these analyses would be the measured rainfall amounts because of possible spatial variability. Greater amounts of water were recovered in surface runoff than in subsurface drainage. Bulk densities of the soil bars did not have a significant effect on storage volumes and recoveries of rainwater.

Tracer Anions Movement and Mass Balance

The concentrations of NO_3-N, Br, and Cl in surface runoff and subsurface drainage versus time for 10 and 15% moisture contents are displayed in Figures 11 through 20. The impacts of soil bulk density and soil moisture content on the average flow-weighted concentrations and losses of NO_3-N, Br, and Cl in surface runoff and subsurface drainage are provided in Tables 6 through 11. In addition, the impact of moisture content and bulk density

on the amount of NO_3-N, Br, and Cl retained by soil and sand are shown in Tables 12 through 14. Mass balances for all tracer anions are shown in Tables 15 through 17. Comparison between three anions on % lost with surface runoff and subsurface drainage is shown in Table 18. The interaction of bulk density with moisture content for NO_3-N loss in subsurface drainage and NO_3-N retained by sand are shown in Figures 21 and 22.

Surface Runoff

Concentrations of NO_3-N in surface runoff were very low, ranging from 0 to 0.5 mg L^{-1} for both 10 and 15% moistures contents. The impacts of soil moisture content and bulk density treatments on NO_3-N flow-weighted runoff concentrations were not significant. Since compacted soil bars with NO_3-N source were placed in the middle of soil pan, 3.8 cm (1.5 in) below the soil surface, and because the compacted soil bar represented only 3% of the soil surface area and at most 0.9% of the soil volume, interaction of surface runoff water with the locally compacted NO_3-N source was not significant. It is likely that most of the NO_3-N in surface runoff was contributed from the soil background source.

The difference in NO_3-N loss in runoff was significant for moisture content treatments ($P=0.0049$), but was not significant for bulk density treatments. Nitrate-nitrogen losses were 0.03 and 0.05 kg ha^{-1} for 10 and 15% moisture treatments, respectively. Not surprisingly, the higher volumes of runoff at 15% moisture caused higher losses of NO_3-N.

There was generally a slight difference in concentration of Br in surface runoff compared to that in rainwater due to dilution of Br in rain water with the water initially in the soil. Concentrations of Br in surface runoff ranged on average between 47 and 52 mg L^{-1} for both 10 and 15% moisture contents, resulting in good agreement with Br concentrations of

50 mg L^{-1} in rain water. According to student's t-test, the impacts of soil moisture content and bulk density on Br flow-weighted runoff concentrations were not significant.

As with NO_3-N, the effect of soil moisture content was significant for Br loss in runoff (P=<0.0001), and effect of bulk density was not significant. Bromide losses in runoff were 16.62 and 25.72 kg ha^{-1} for 10 and 15% moisture treatments, respectively, reflecting similar trends in runoff volumes.

The Cl concentrations and losses in surface runoff were below detection limits. Due to Br interference in runoff samples, values for Cl concentration were adjusted, resulting in values below 1.0 mg L^{-1}, the detectable limit.

Subsurface Drainage

The impact of bulk density on flow-weighted NO_3-N concentrations in subsurface drainage was significant (P=0.0009). The concentrations of NO_3-N in subsurface drainage averaged over 10 and 15% moisture contents were 130.5, 176.8, 432.2, 656.3 mg L^{-1} and were in the order of 1.81<1.57<1.33<1.10 g cm^{-3} bulk density treatments. According to the LSD test, concentrations for 1.81 and 1.57 g cm^{-3} were significantly different from those for 1.33 and 1.10 g cm^{-3}.

Differences in NO_3-N losses in subsurface drainage were significant for both moisture content (P=0.0004) and bulk density (P=0.0004). Losses averaged over bulk density treatments were 63.73 and 20.73 kg ha^{-1} and were in the order of 10>15% moisture content, and losses averaged over 10 and 15% moisture contents were 12.07, 21.08, 53.63, and 82.13 kg ha^{-1} and were in order of 1.81<1.57<1.33<1.10 g cm^{-3} bulk density. Higher losses of NO_3-N for 10% moisture content reflected higher volumes of subsurface drainage at that moisture. In addition, the LSD test showed that the differences between 1.81 and 1.33 and 1.10 g cm^{-3}

bulk densities were much greater than those between 1.81 and 1.57. This suggested that the higher the bulk density, the greater the impact on reduction of NO_3-N losses in subsurface drainage.

The interaction of moisture content with bulk density had a significant effect (P=0.0315) on NO_3-N loss in subsurface drainage, resulting in significant reduction of NO_3-N loss with higher moisture content and higher bulk density.

The impact of soil moisture content on Br flow-weighted concentrations in subsurface drainage was significant (P=<0.0001). The concentrations of Br in subsurface drainage were 49.25 and 21.82 mg L^{-1} and were in order of 10>15% moisture content. Since Br was applied in rainwater, it reflected similar trends to volumes of surface and subsurface drainage. Since 10% moisture created less surface runoff and more subsurface drainage, it resulted in greater Br concentrations in subsurface drainage.

Differences in Br loss in subsurface drainage were significant (P=<0.0001) for moisture content and not significant for bulk density. Bromide losses in subsurface drainage were 8.31 and 1.49 kg ha^{-1}, the highest being at 10% moisture treatment, which reflected the hydrological trend of higher volumes of drainage at that moisture content.

The impact of soil moisture content on flow-weighted Cl concentrations in subsurface drainage was significant (P=<0.0001). The concentrations of Cl in subsurface drainage were 675 and 1256 mg L^{-1} and were in order of 10<15% moisture content. At the beginning of subsurface drainage, Cl concentrations were higher at 10% moisture than at 15%; however, as drainage continued, the Cl concentrations in subsurface drainage reduced very quickly at 10% moisture and remained more stable at 15%. Since Cl was incorporated into the soil, lesser volumes of drainage water at 15% moisture resulted in greater concentrations, while

greater volumes of drainage water at 10% moisture, resulted in smaller concentrations. Because the compacted soil bar was a very small fraction of the soil volume in the pan, the impact of bulk density on Cl concentrations in subsurface drainage was not significant.

Chloride losses in subsurface drainage were 112 and 78 kg ha^{-1} for 10 and 15% moisture contents, respectively. Effect of moisture content was significant (P=<0.0001), with greater losses at 10% moisture content. Since bulk density treatments in compacted soil bars were at most only 0.9% of the soil volume, bulk density did not have a significant effect on Cl losses in subsurface drainage.

Storage

Moisture content and bulk density had significant effects on the amount of NO_3-N retained in soil and sand. The amounts retained in soil averaged over bulk density treatments were 46.5 and 77.0 kg ha^{-1} and were in the order of 10<15% for moisture content treatments, and the amounts averaged over 10 and 15% moisture content treatments were 90.35, 87.62, 42.35, and 26.82 kg ha^{-1} and were in order of 1.10<1.33<1.57<1.81 g cm^{-3} for bulk density treatments. The amounts retained by sand were 4.0 and 14.8 kg ha^{-1} and were in the same order to that retained by soil, 10<15% for moisture content treatments, and were 2.72, 4.29, 16.20, and 14.46 kg ha^{-1} and were opposite in order to that retained by soil, 1.81<1.57<1.10<1.33 g cm^{-3} for bulk density treatments. Since the compacted bar with NO_3-N was placed within the soil, greater storage of NO_3-N in the soil suggested lesser leaching to subsurface drainage and thus less stored in sand. Similarly, greater storage of NO_3-N in sand suggested greater leaching of NO_3-N to subsurface drainage and less storage in the soil. The interaction effect of bulk density with moisture content (P=<0.0001) had significant

effect on the amount of NO_3-N retained by sand. Therefore, higher bulk density and higher moisture content of soil indicated less NO_3-N leaching into subsurface drainage.

The effect of moisture content on the anion amounts retained by soil was significant for both Br (P=0.0049) and Cl (P=0.0003); however, the effect of moisture content on the amount retained by sand was significant only for Cl (P=<0.0001). Bromide amounts retained by soil were 10.24 and 9.47 kg ha^{-1} and were in the order of 15<10% moisture content. Since the Br source was in the rainwater, its loss was reflected in the trend of greater volumes of subsurface drainage for the 10% moisture content, where more water passed through the soil and carried greater amounts of Br with it. However, Cl amounts retained by soil were 3.59 and 11.13 kg ha^{-1} and were in the order of 10<15% moisture treatments. Similarly, Cl retained by sand were 3.28 and 28.70 kg ha^{-1} for 10 and 15% moisture content treatments.

Table 1. Times to beginnings of surface runoff and subsurface drainage. †

	Moisture Content	Bulk Density (g cm^{-3}) 1.10	1.33	1.57	1.81	Average
	%	----------min----------				
Surface Runoff	10	21.7	22.0	21.0	22.7	21.8a
	15	11.3	11.3	12.0	10.3	11.3b
Average		16.5a	16.7a	16.5a	16.5a	
SubSurface Drainage	10	28.7	28.7	28.7	28.7	28.7a
	15	43.3	44.3	42.0	45.0	43.7b
Average		36.0a	36.5a	36.3a	36.8a	

† Means with the same letter are not significantly different at the α=0.05 level.

Table 2. Water mass balance †

Moisture Content (%)	Bulk Density (g cm^{-3})	Rainfall Quantity (cm)	Subsurface Drainage (cm)	Runoff Quantity (cm)	Stored in Soil (cm)	Stored in Sand (cm)	Collected Quantity ♠ (cm)	Difference ♣ (cm)
10	1.10	7.62	1.70	3.53	2.38	0.39	8.28	0.65
10	1.33	7.64	1.82	3.24	2.25	0.37	7.92	0.28
10	1.57	7.57	1.65	3.24	2.27	0.34	7.76	0.19
10	1.81	7.56	1.60	3.38	2.37	0.40	7.91	0.35
15	1.10	7.80	0.69	5.18	1.57	0.42	8.07	0.27
15	1.33	7.82	0.57	4.98	1.60	0.41	7.75	-0.07
15	1.57	7.92	0.68	4.90	1.55	0.41	7.88	-0.03
15	1.81	7.94	0.56	5.31	1.49	0.41	8.01	0.07

† Soil surface area =3281 cm^2

♠ The sum of drainage, runoff, and stored quantities.

♣ Numbers with negative sign in this column indicate shortage of water

Table 3. Moisture content and water storage in soil and sand

Initial Soil Moisture Content (%)	Bulk Density (g/cm^3)	Rep	Soil Storage (cm)	Final Soil M. C. (Measured) (%) *	TDR ⸮ measured soil M.C. (%) *	Sand Storage (cm)	Final Sand M. C. (Measured) (%)	Final Sand M.C. (Calculated) (%)
10	1.10	1	2.43	38.45	36.10	0.72	17.67	19.65
		2	2.28	37.61	34.00	0.63	--	17.23
		3	2.42	38.20	38.20	0.66	--	18.06
	1.33	1	2.26	37.16	35.30	0.69	--	18.63
		2	2.23	36.97	34.90	0.57	--	15.40
		3	2.27	37.11	35.00	0.56	--	15.31
	1.57	1	2.21	36.54	35.20	0.54	--	14.56
		2	2.30	36.76	35.10	0.59	--	16.00
		3	2.31	37.58	35.70	0.67	--	18.31
	1.81	1	2.44	38.47	36.20	0.65	18.14	17.55
		2	2.31	36.84	34.80	0.51	--	13.74
		3	2.36	37.51	36.20	0.55	--	14.83
Mean			2.32a	37.43a	35.56a	0.61a		
15	1.10	1	1.53	34.10	29.30	0.65	--	17.56
		2	1.54	33.59	31.00	0.78	--	21.14
		3	1.63	34.09	29.60	0.49	17.17	13.36
	1.33	1	1.61	34.11	30.10	0.55	--	14.91
		2	1.61	34.40	31.70	0.61	--	16.64
		3	1.57	33.33	31.50	0.64	17.58	17.30
	1.57	1	1.55	34.45	32.40	0.68	--	18.48
		2	1.56	34.41	30.80	0.55	--	15.08
		3	1.53	34.57	31.50	1.02	17.21	27.84
	1.81	1	1.59	33.86	30.70	0.48	--	13.16
		2	1.56	34.38	32.00	0.84	--	22.93
		3	1.32	31.96	29.70	0.65	17.14	17.72
Mean			1.55b	33.94b	30.86b	0.66a		

⸮ TDR - Time Domain Refloctometry, a device to measure soil moisture content. Data obtianed from Zian Zhou

* Correlation between mesured final soil moisture content and TDR measured values

10% moisture treatment: $y = 0.9816X-1.1856$ and $R^2 = 0.3727$ ($P=0.035$)

15% moisture treatment: $y = 0.5797X+11.184$ and $R^2 = 0.1736$ ($P=0.177$)

Table 4. Average rainfall volumes and volume of water stored and drained.†

	Moisture Content	Bulk Density (g/cm^3)				
		1.10	1.33	1.57	1.81	Mean
	%	cm				
Rainfall	10	7.56	7.57	7.64	7.62	7.60a
	15	7.94	7.92	7.82	7.80	7.90a
Mean		7.71a	7.73a	7.74a	7.75a	
Surface Runoff	10	3.38	3.24	3.24	3.53	3.35b
	15	5.31	4.90	4.98	5.18	5.10a
Mean		4.35a	4.11a	4.10a	4.34a	
Subsurface drainage	10	1.60	1.65	1.82	1.70	1.69a
	15	0.56	0.68	0.57	0.69	0.62b
Mean		1.19a	1.20a	1.17a	1.10a	
Storage in soil	10	2.38	2.25	2.27	2.37	2.32a
	15	1.57	1.60	1.55	1.49	1.55b
Mean		1.97a	1.92a	1.91a	1.93a	
Storage in sand	10	0.67	0.61	0.60	0.57	0.61a
	15	0.64	0.60	0.75	0.66	0.66a
Mean		0.40a	0.39a	0.38a	0.40a	

† Means with the same letter in each column are not significantly different at the α=0.05 level.

Table 5. Hydrologic/Infiltration analysis for moisture content effects

From	To	Runoff Time (min)	Drainage Time (min)
10% m.c.	Runoff/Drainage	21.8	28.7
10% m.c.	15% m.c.	3.9	3.9
15% m.c.	Runoff/Drainage	11.3	43.7
10% m.c.	Predicted Runoff/Drainage £	15.2	47.6
Difference		6.6	-19.1

£ Predicted is time to wet 10% to 15% plus time to runoff/drainage for 15%

Table 6. Flow-weighted NO_3-N concentrations in surface runoff and subsurface drainage†

	Moisture Content	Bulk Density (g cm^{-3}) 1.10	1.33	1.57	1.81	Mean
	%	---------- mg L^{-1} ----------				
Flow-Weighted Surface Runoff Concentration	10	0.13	0.10	0.06	0.07	0.09a
	15	0.11	0.10	0.11	0.08	0.10a
Mean		0.12a	0.10a	0.09a	0.07a	
Flow-Weighted Subsurface Drainage Concentration	10	751.23	430.19	200.27	91.77	368.37a
	15	561.29	434.29	153.38	169.23	329.55a
Mean		656.30a	432.20a	176.80b	130.50b	

† Means with the same letter are not significantly different at the α=0.05 level.

Table 7. Flow-weighted Br concentrations in surface runoff and subsurface drainage†

	Moisture Content	Bulk Density (g cm^{-3})				
		1.10	1.33	1.57	1.81	Mean
	%	---------- $mg\ L^{-1}$ ----------				
Flow-Weighted Surface Runoff Concentration	10	49.76	50.68	49.98	48.25	49.67a
	15	49.94	51.14	49.68	50.33	50.27a
Mean		49.85ab	50.90a	49.83ab	49.29b	
Flow-Weighted Subsurface Drainage Concentration	10	49.36	49.42	50.30	47.91	49.25a
	15	21.49	18.79	27.22	19.79	21.82b
Mean		35.42a	34.11a	38.76a	33.85a	

† Means with the same letter are not significantly different at the α=0.05 level.

Table 8. Flow-weighted Cl concentrations in surface runoff and subsurface drainage†

	Moisture Content	Bulk Density (g cm^{-3})				
		1.10	1.33	1.57	1.81	Mean
	%	---------- $mg\ L^{-1}$ ----------				
Flow-Weighted Surface Runoff Concentration	10	Below Detection				
	15					
Mean						
Flow-Weighted Subsurface Drainage Concentration	10	694.46	604.49	679.36	721.50	674.96b
	15	1196.45	1307.18	1163.07	1357.47	1256.04a
Mean		945.46a	955.84a	921.22a	1039.49a	

† Means with the same letter are not significantly different at the α=0.05 level.

Table 9. NO_3-N losses in surface runoff and subsurface drainage†

	Moisture Content	Bulk Density (g cm^{-3})				
		1.10	1.33	1.57	1.81	Mean
	%	---------- kg ha^{-1} ----------				
Surface Runoff Loss	10	0.04	0.03	0.02	0.02	0.03b
	15	0.06	0.05	0.06	0.04	0.05a
Mean		0.05a	0.04ab	0.04ab	0.03b	
Subsurface Drainage Loss	10	125.87	82.75	31.58	14.70	63.73a
	15	38.38	24.52	10.58	9.43	20.73b
Mean		82.13a	53.63b	21.08c	12.07c	

† Means with the same letter are not significantly different at the α=0.05 level.

Table 10. Br losses in surface runoff and subsurface drainage†

	Moisture Content	Bulk Density (g cm^{-3})				
		1.10	1.33	1.57	1.81	Mean
	%	---------- kg ha^{-1} ----------				
Surface Runoff Loss	10	17.56	16.40	16.22	16.31	16.62b
	15	25.86	25.44	24.30	26.77	25.72a
Mean		21.71a	20.92a	20.51a	21.54a	
Subsurface Drainage Loss	10	8.38	8.93	8.28	7.67	8.31a
	15	1.58	1.07	1.91	1.20	1.49b
Mean		4.98a	5.09a	5.09a	4.44a	

† Means with the same letter are not significantly different at the α=0.05 level.

Table 11. Cl losses in surface runoff and subsurface drainage†

	Moisture Content	Bulk Density (g cm^{-3}) 1.10	1.33	1.57	1.81	Mean
	%	----------kg ha^{-1} ----------				
Surface Runoff Loss	10	Below Detection				
	15					
Mean						
Subsurface Drainage Loss	10	115.56	108.16	111.00	115.48	112.55a
	15	78.49	82.84	80.25	73.93	78.88b
Mean		97.02a	95.50a	95.62a	94.71a	

† Means with the same letter are not significantly different at the α=0.05 level.

Table 12. NO_3-N retained by soil and sand in the pan†

	Moisture Content	Bulk Density (g cm^{-3}) 1.10	1.33	1.57	1.81	Mean
	%	----------kg ha^{-1} ----------				
Retained by Soil	10	2.96	22.66	77.81	82.55	46.49b
	15	50.68	61.84	97.44	98.15	77.03a
Mean		26.82b	42.35b	87.62a	90.35a	
Retained by Sand	10	4.41	6.59	3.94	1.09	4.01b
	15	24.50	25.80	4.63	4.35	14.82a
Mean		14.46a	16.20a	4.29b	2.72b	

† Means with the same letter are not significantly different at the α=0.05 level.

Table 13. Br retained by soil and sand in the pan†

	Moisture Content	Bulk Density (g cm^{-3})				
		1.10	1.33	1.57	1.81	Mean
	%	---------- kg ha^{-1} ----------				
Retained by Soil	10	10.07	9.95	10.65	10.30	10.24a
	15	9.32	10.30	9.55	8.72	9.47b
Mean		9.70a	10.12a	10.10a	9.51a	
Retained by Sand	10	2.76	2.39	2.35	2.51	2.50a
	15	2.19	2.23	2.56	2.14	2.28a
Mean		2.47a	2.31a	2.45a	2.33a	

† Means with the same letter are not significantly different at the α=0.05 level.

Table 14. Cl retained by soil and sand in the pan†

	Moisture Content	Bulk Density (g cm^{-3})				
		1.10	1.33	1.57	1.81	Mean
	%	---------- kg ha^{-1} ----------				
Retained by Soil	10	2.42	2.64	4.80	4.49	3.59b
	15	11.83	9.33	10.52	12.83	11.13a
Mean		7.13a	5.99a	7.66a	7.66a	
Retained by Sand	10	3.78	2.82	3.35	3.16	3.28b
	15	29.62	30.16	26.27	28.71	28.70a
Mean		16.70a	16.49a	14.81a	15.93a	

† Means with the same letter are not significantly different at the α=0.05 level.

Table 15. NO_3-N mass balance

Moisture Content	Bulk Density	Surface Runoff	Retained by Soil	Retained by Sand	Sub-Surface Drainage	Initial soil total ±	Total recovered	Difference
%	g cm^{-3}				kg ha^{-1}			
10	1.10	0.04	2.96	4.41	125.87	116.87	133.29	-14.13
	1.33	0.03	22.66	6.59	82.75	117.18	112.04	4.06
	1.57	0.02	77.81	3.94	31.58	117.75	113.35	3.75
	1.81	0.02	82.55	1.09	14.70	117.44	98.37	16.37
15	1.10	0.06	50.68	24.50	38.38	125.36	113.63	9.24
	1.33	0.05	61.84	25.80	24.52	125.40	112.20	10.40
	1.57	0.06	97.44	4.63	10.58	125.56	112.71	10.14
	1.81	0.04	98.15	4.35	9.43	125.60	111.97	10.72

± 112 kg ha^{-1} added in compacted soil bar; remainder from that in soil originally.

Table 16. Br mass balance

Moisture Content	Bulk Density	Surface Runoff	Retained by Soil	Retained by Sand	Sub-Surface Drainage	Initial total ±	Total recovered	Difference
%	g cm^{-3}				kg ha^{-1}			
10	1.10	17.56	10.07	2.76	8.38	35.83	38.77	-8.52
	1.33	16.40	9.95	2.39	8.93	38.53	37.67	2.12
	1.57	16.22	10.65	2.35	8.28	38.56	37.50	2.62
	1.81	16.31	10.30	2.51	7.67	38.91	36.80	4.88
15	1.10	25.86	9.32	2.19	1.58	38.91	38.95	-0.22
	1.33	25.44	10.30	2.23	1.26	39.93	39.23	1.79
	1.57	24.80	9.55	2.56	1.91	39.26	38.82	1.05
	1.81	26.77	8.72	2.14	1.20	39.88	38.83	2.71

± With rainwater (amount in soil <2.0 kg ha^{-1})

Table 17. Cl mass balance

Moisture Content	Bulk Density	Surface Runoff	Retained by Soil	Retained by Sand	Sub-Surface Drainage	Initial soil total ±	Total recovered	Difference
%	g cm^{-3}				kg ha^{-1}			
10	1.10	--	2.42	3.78	115.56	121.04	121.76	-0.55
	1.33	--	2.64	2.82	108.16	122.22	113.62	6.93
	1.57	--	4.80	3.35	111.00	122.86	119.14	2.91
	1.81	--	4.49	3.16	115.48	121.72	123.13	-1.34
15	1.10	--	11.83	29.62	78.49	121.18	119.94	1.01
	1.33	--	9.33	30.16	82.84	120.45	122.33	-1.57
	1.57	--	10.52	26.27	80.25	119.65	117.04	2.18
	1.81	--	12.83	28.71	73.93	118.16	115.47	2.17

± 112 kg ha^{-1} added before soil pans were packed; remainder from that in soil originally.

Table 18. Comparison between three anions on % lost from initial soil total

Anion	Bulk density	10% Surface Runoff	10% Sub-Surface Drainage	15% Surface Runoff	15% Sub-Surface Drainage
	g cm^{-3}	----------	%	----------	
NO_3-N	1.10	0.04	107.71	0.05	30.62
	1.33	0.03	70.62	0.04	19.55
	1.57	0.02	26.82	0.04	8.43
	1.81	0.02	12.52	0.03	7.51
Br ±	average	43.90	21.94	65.12	3.77
Cl	average	--	92.30	--	65.80

± Comparison for Br is based on the amount of Br actually entering the soil through infiltrating rainwater (plus small amount initially present)

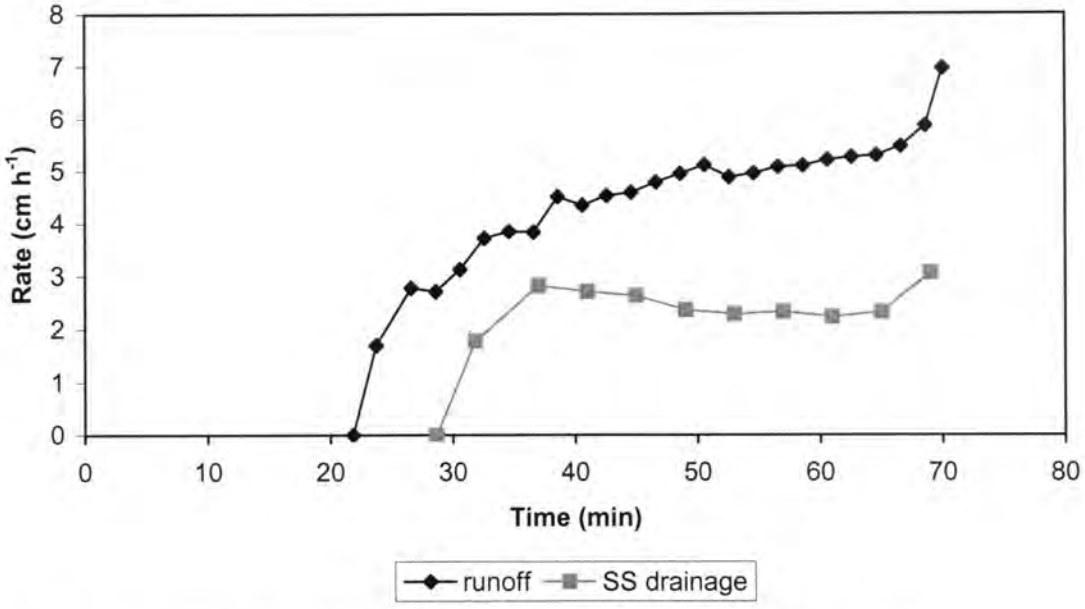

Figure 1. Surface runoff and subsurface drainage rates from treatment 10-1.10

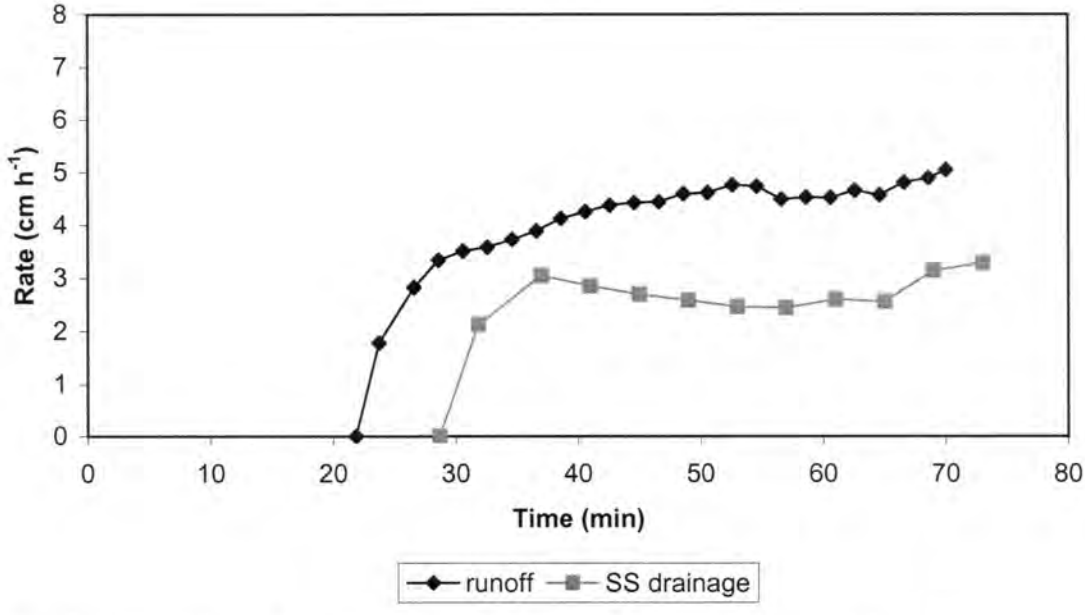

Figure 2. Surface runoff and subsurface drainage rates from treatment 10-1.33

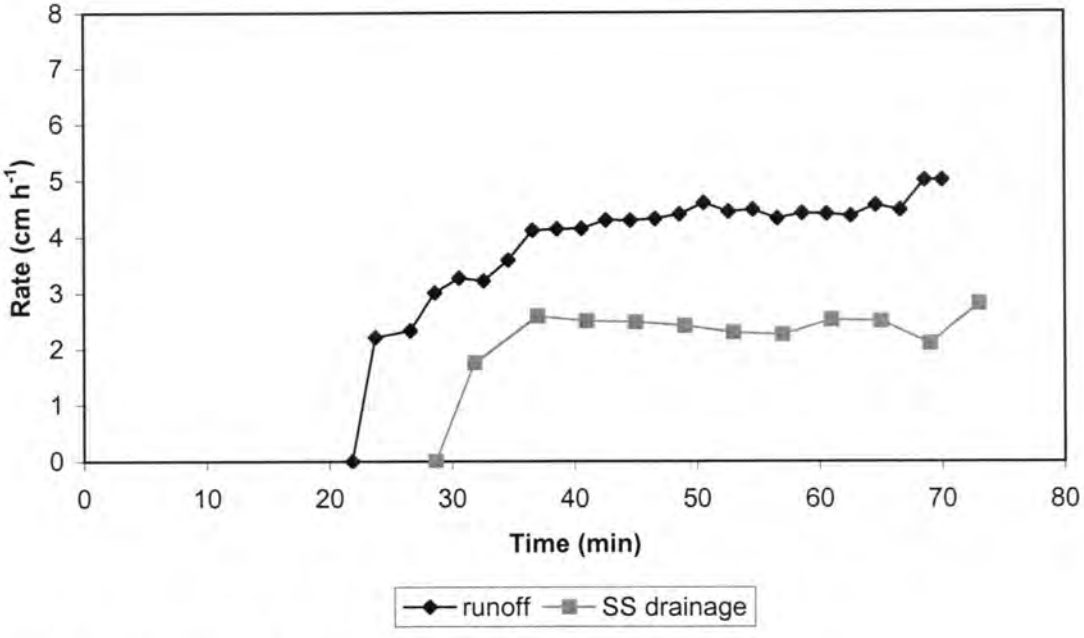

Figure 3. Surface runoff and subsurface drainage rates from treatment 10-1.57

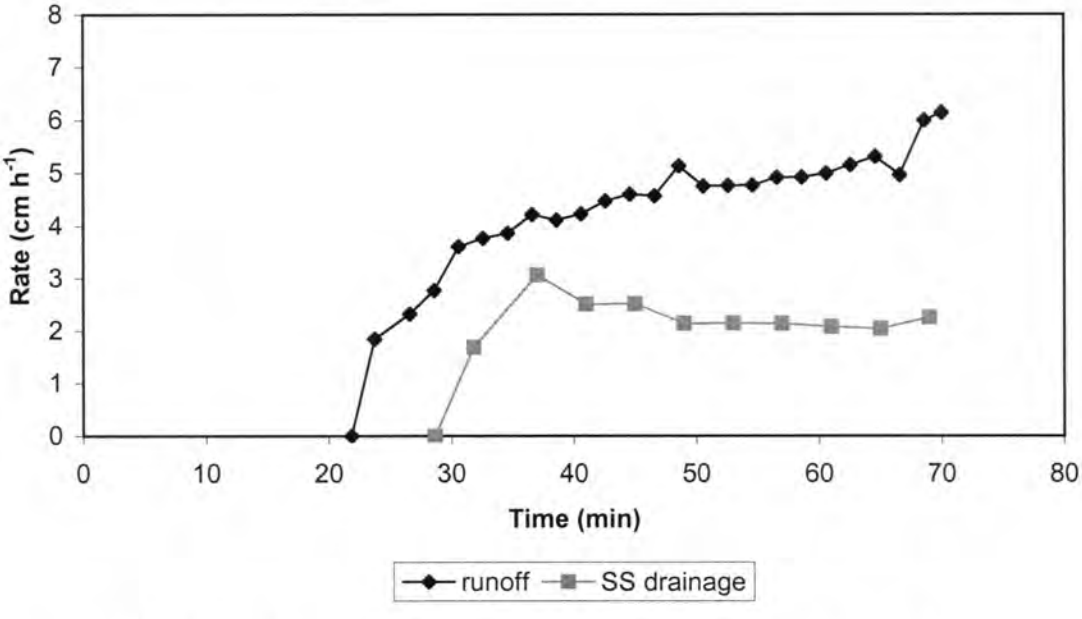

Figure 4. Surface runoff and subsurface drainage rates from treatment 10-1.81

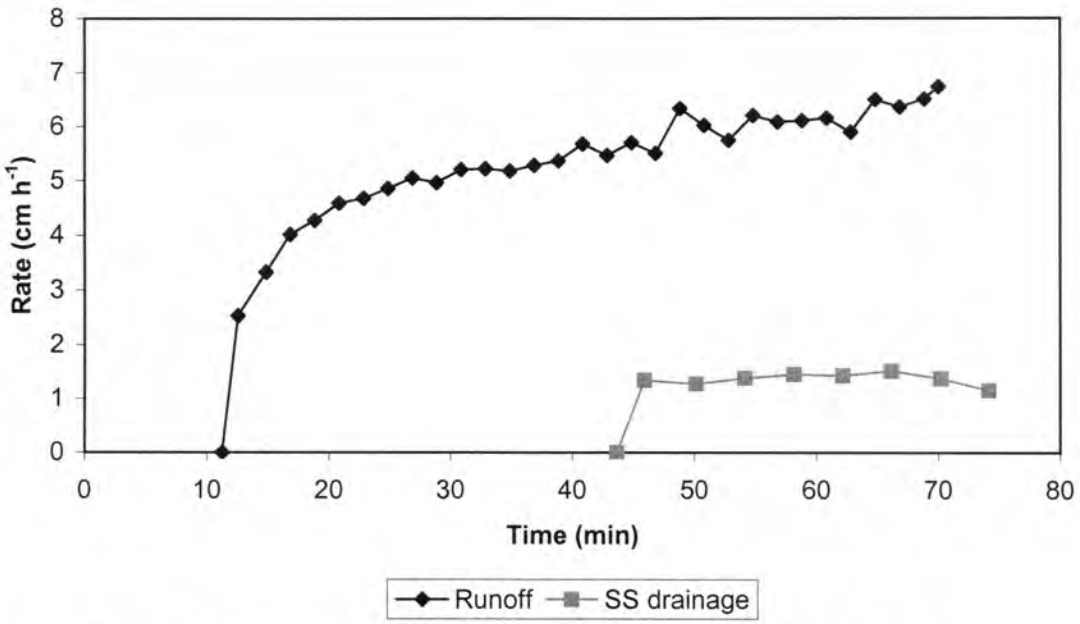

Figure 5. Surface runoff and subsurface drainage rates from treatment 15-1.10

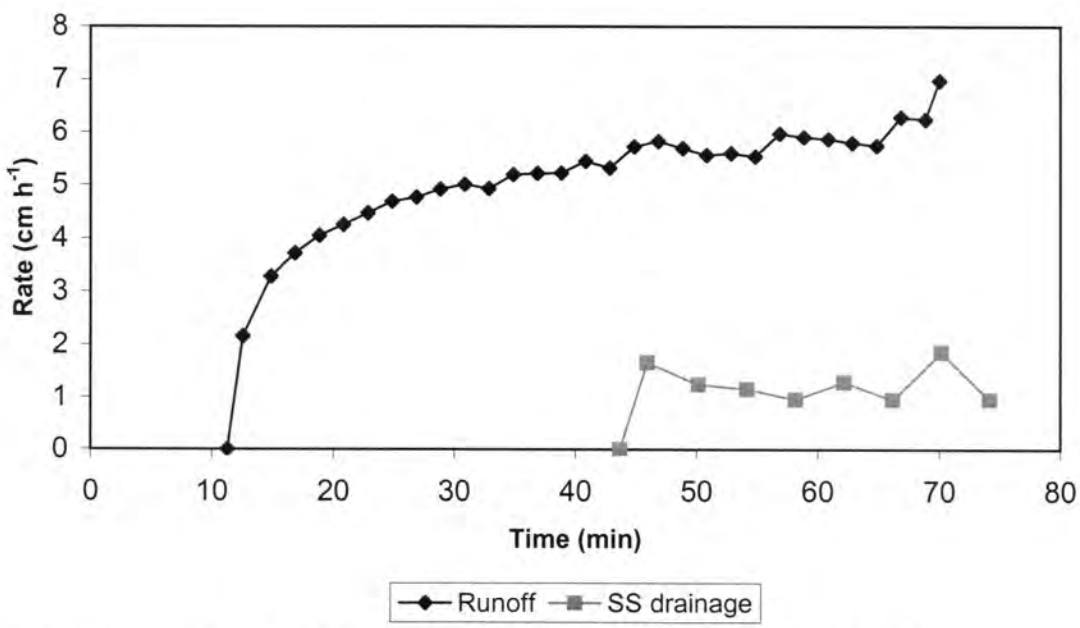

Figure 6. Surface runoff and subsurface drainage rates from treatment 15-1.33

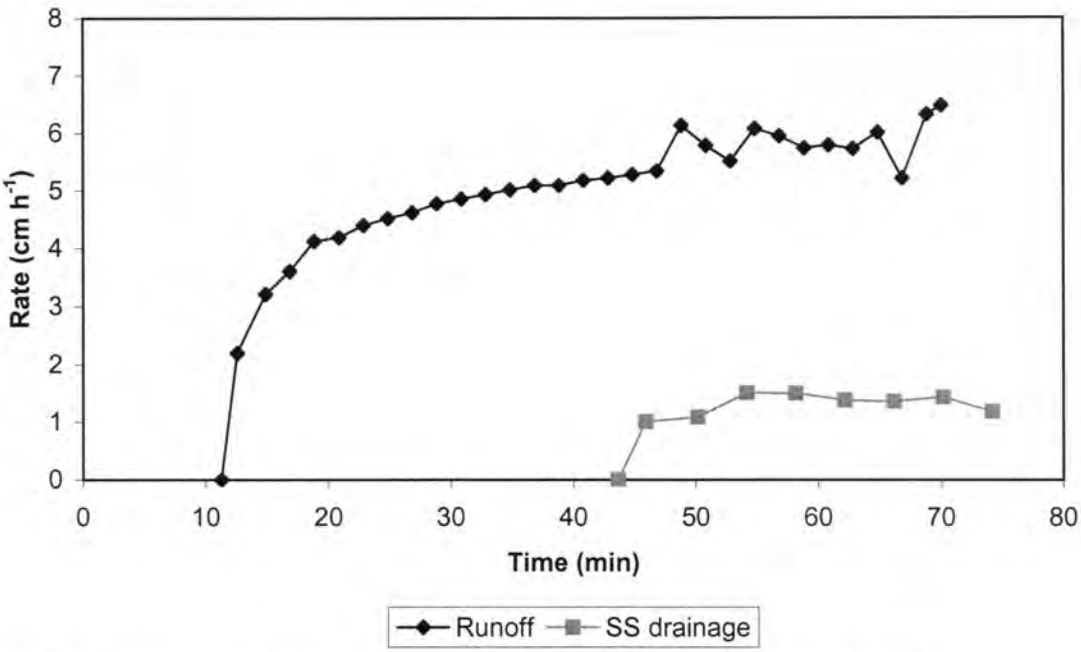

Figure 7. Surface runoff and subsurface drainage rates from treatment 15-1.57

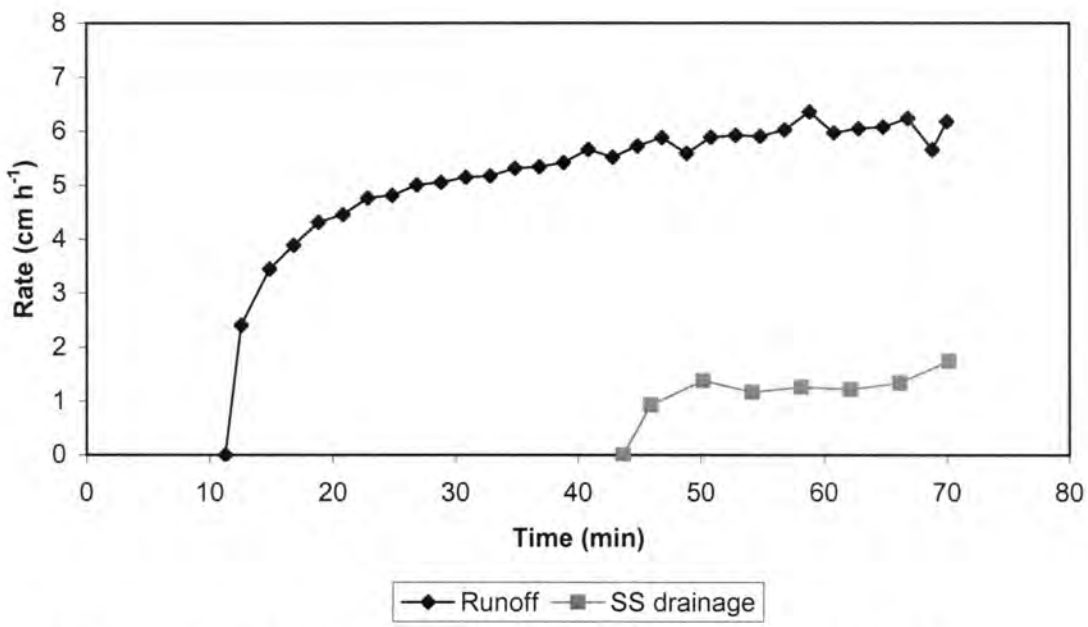

Figure 8. Surface runoff and subsurface drainage rates from treatment 15-1.81

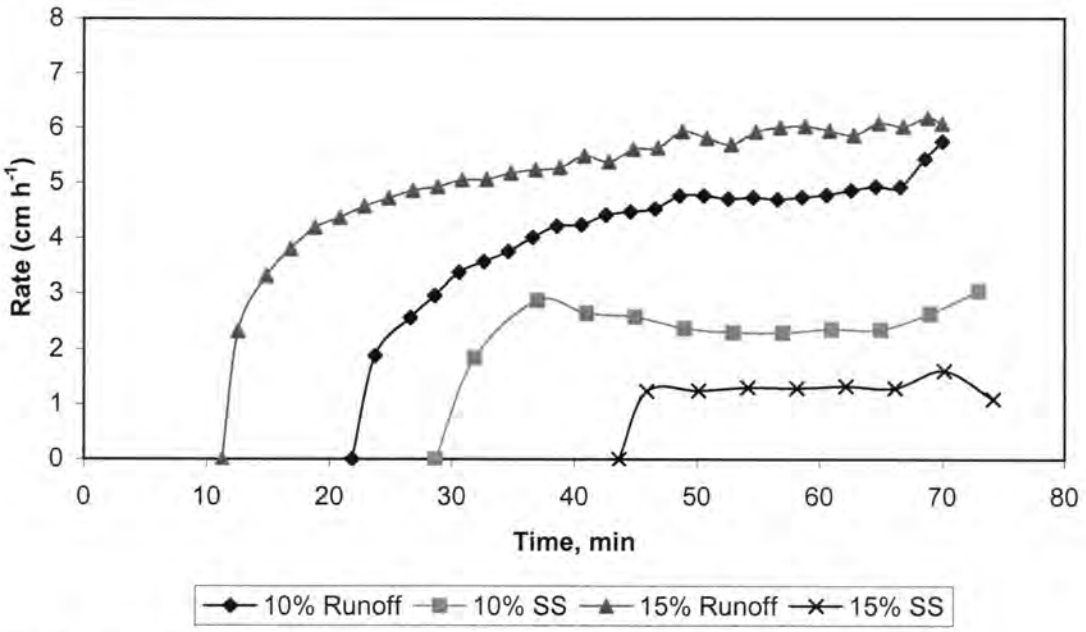

Figure 9. Average surface runoff and subsurface drainage rates for 10 and 15% moisture content

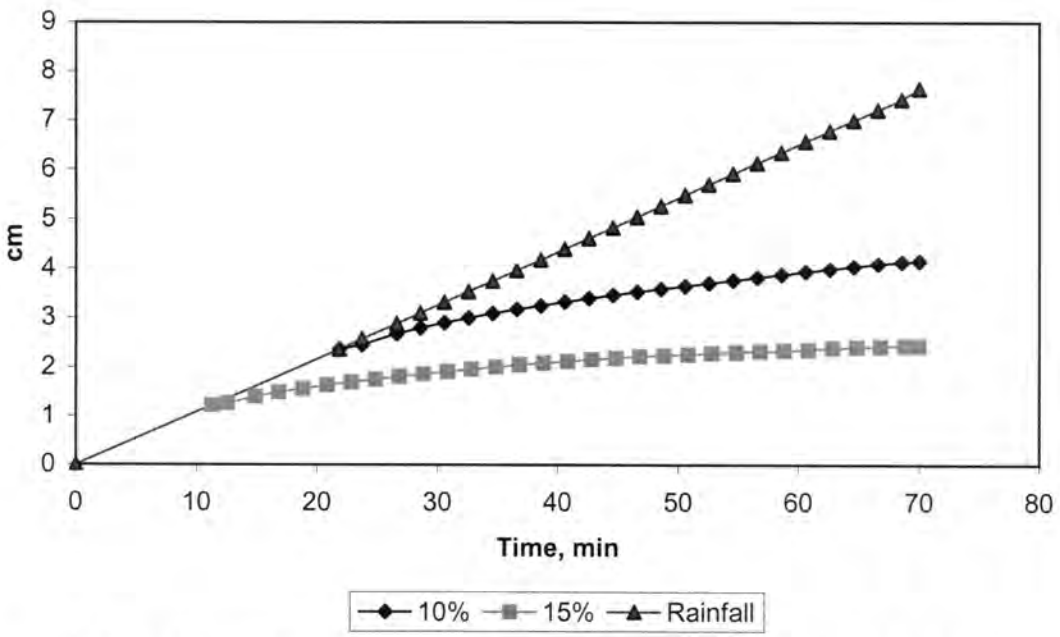

Figure 10. Cumulative infitration for 10 and 15% moisture and cumulative rainfall

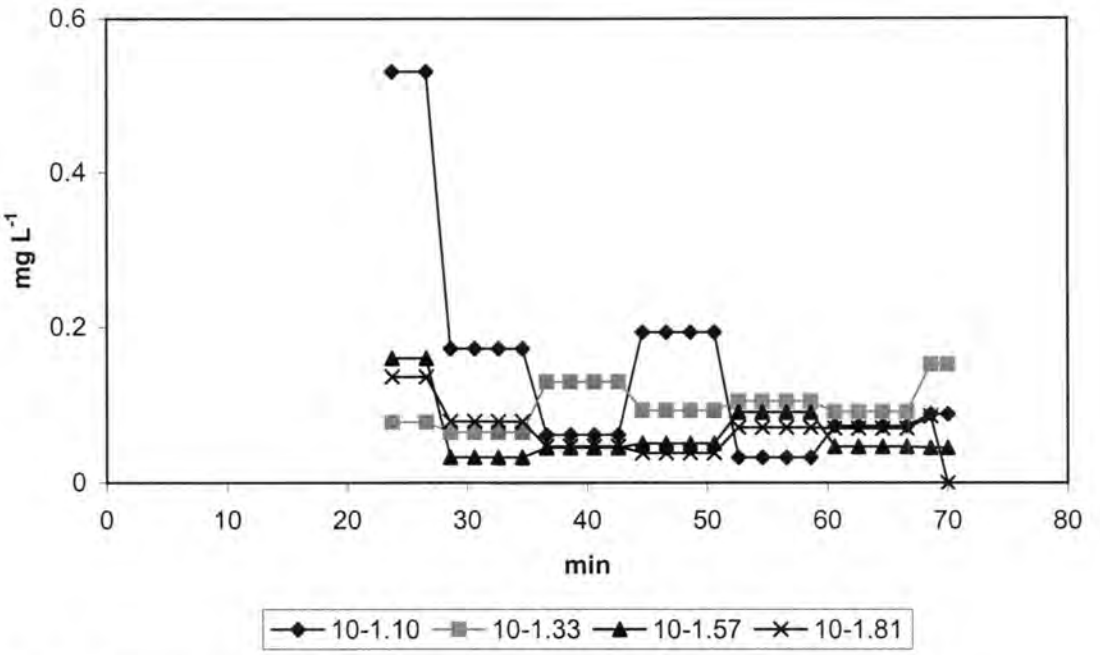

Figure 11. Concentration of NO_3-N in surface runoff versus time for 10% moisture

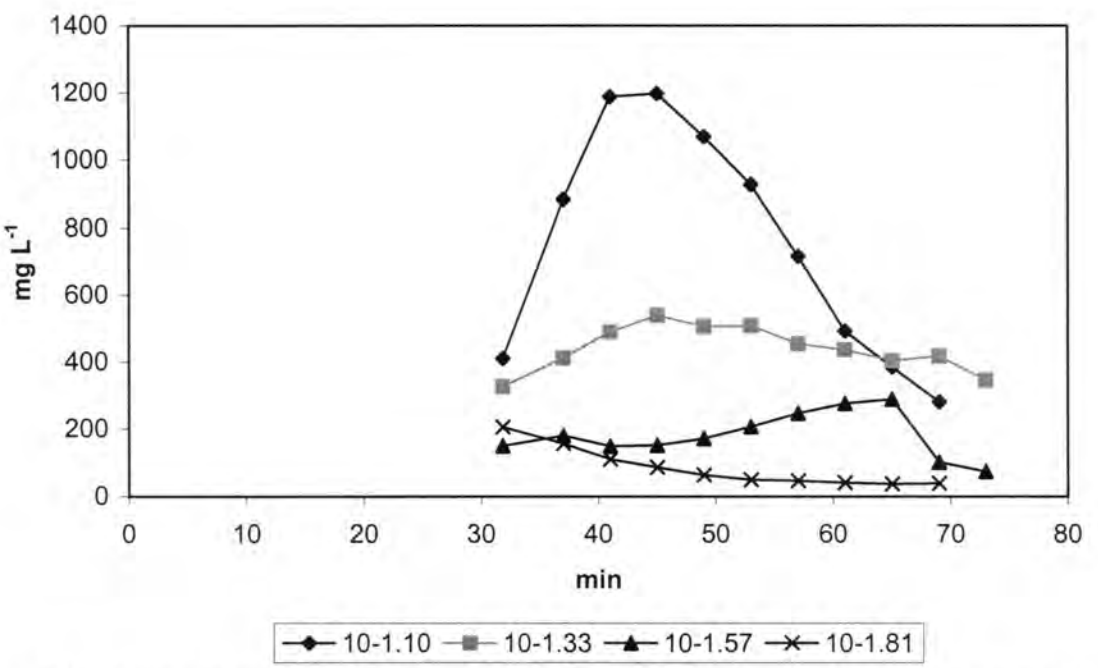

Figure 12. Concentration of NO_3-N in subsurface drainage versus time for 10% moisture

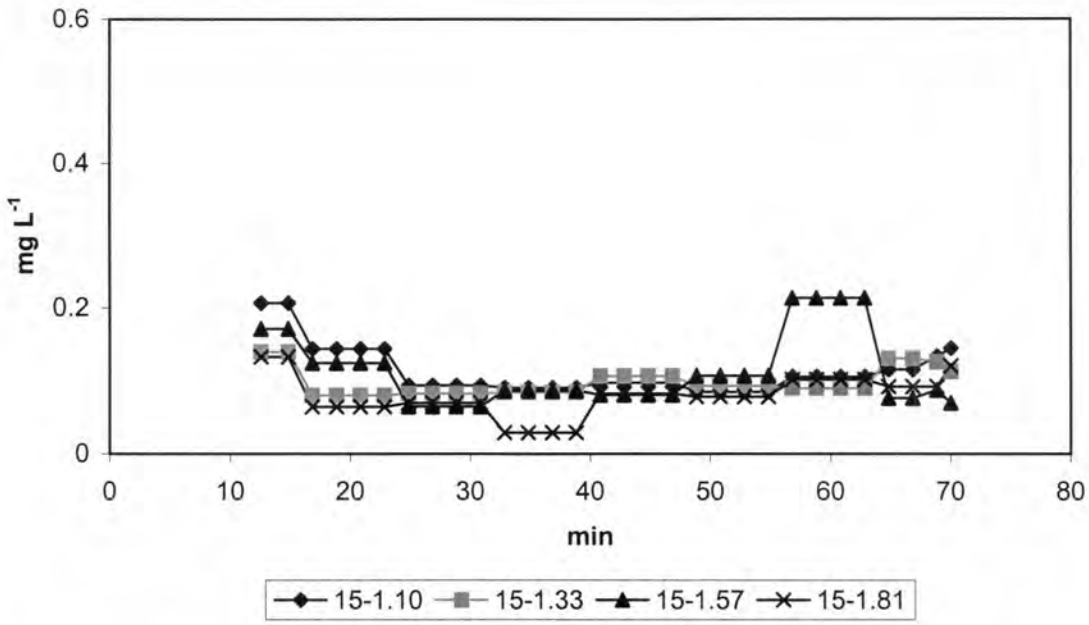

Figure 13. Concentration of NO_3-N in surface runoff versus time for 15% moisture

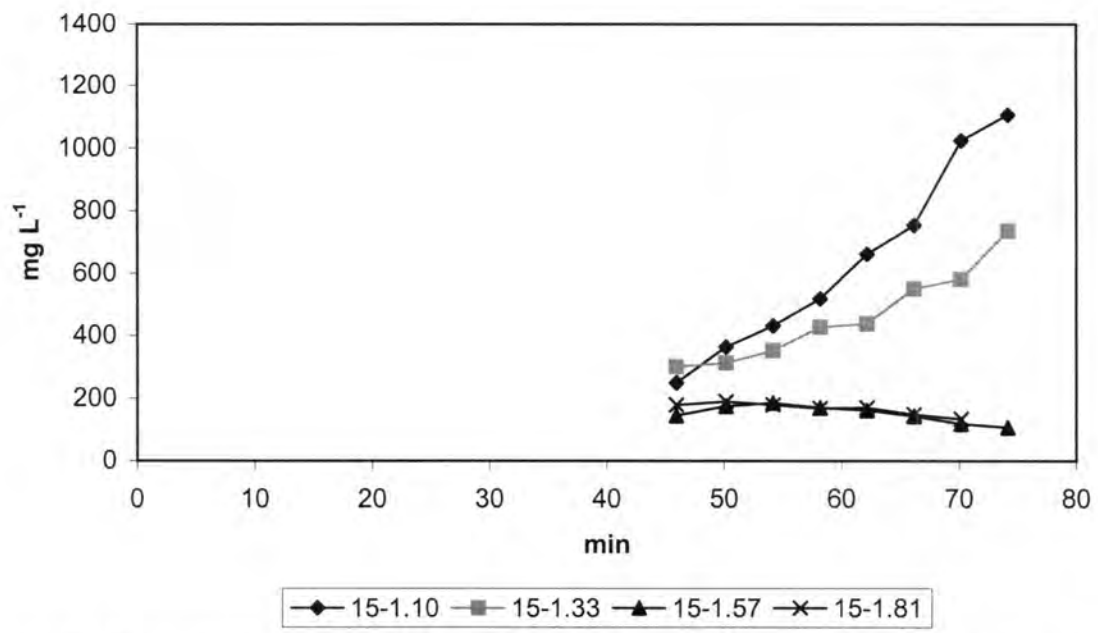

Figure 14. Concentration of NO_3-N in subsurface drainage versus time for 15% moisture

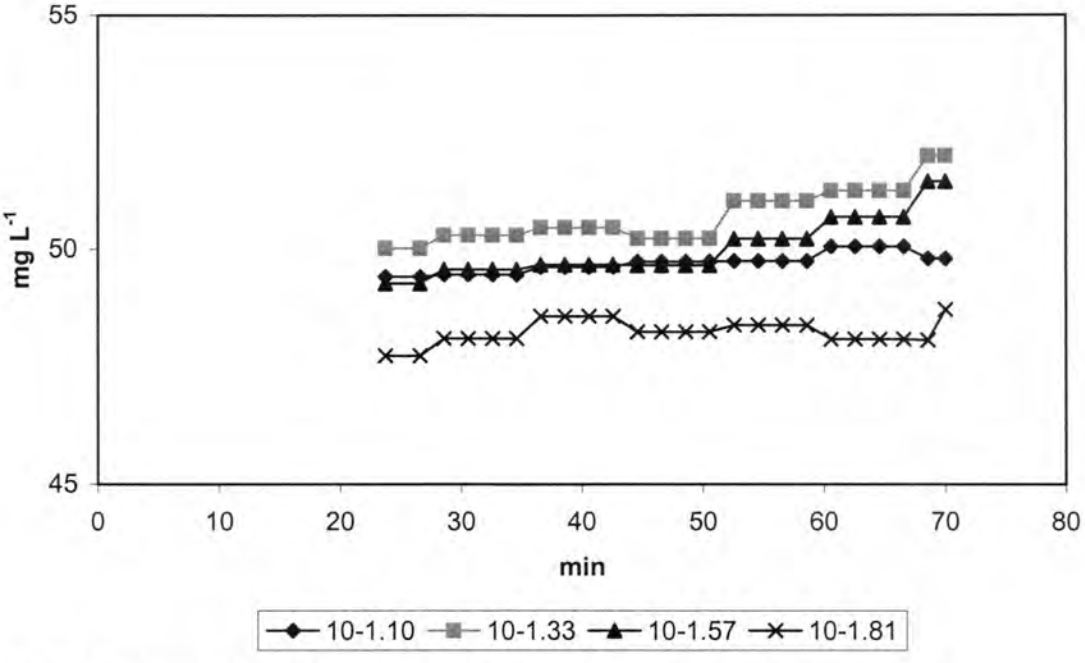

Figure 15. Concentration of Br in surface runoff versus time for 10% moisture

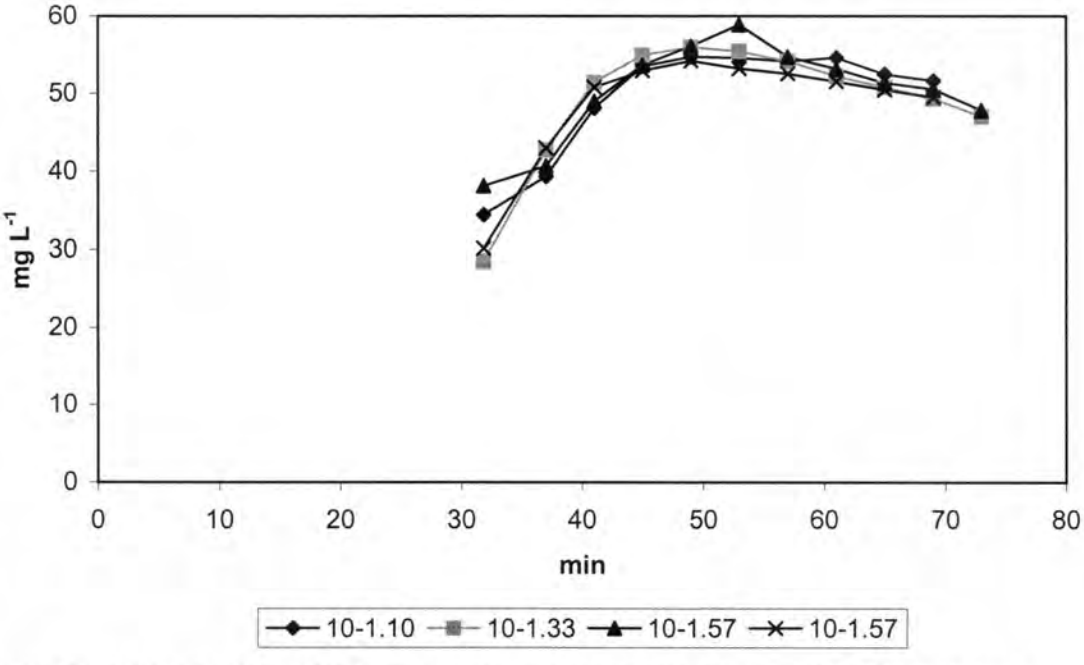

Figure 16. Concentration of Br in subsurface drainage versus time for 10% moisture

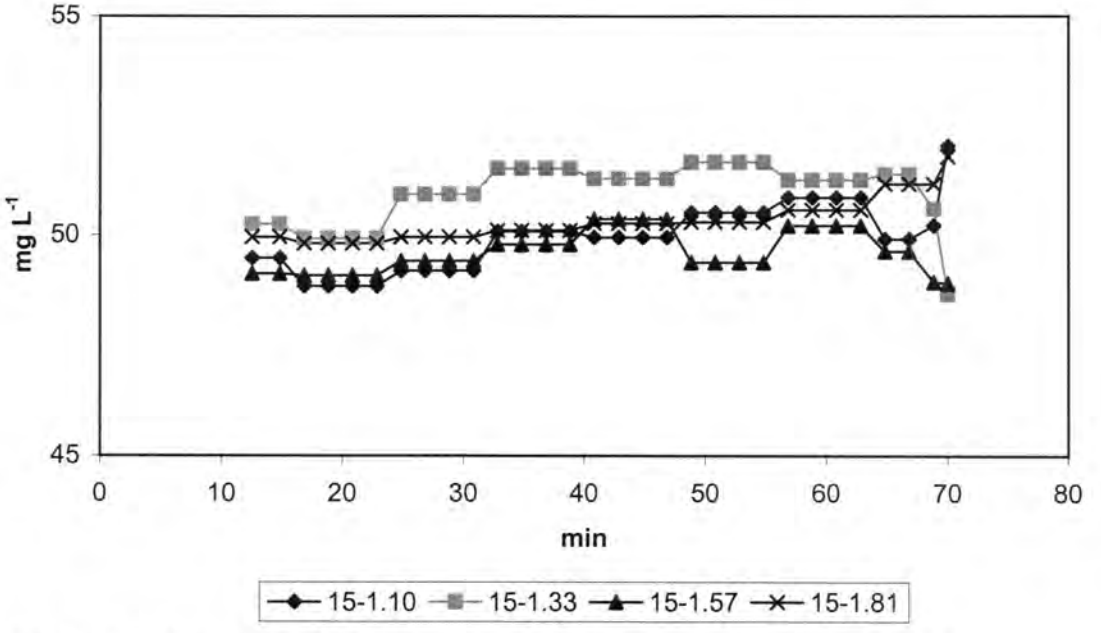

Figure 17. Concentration of Br in surface runoff versus time for 15% moisture

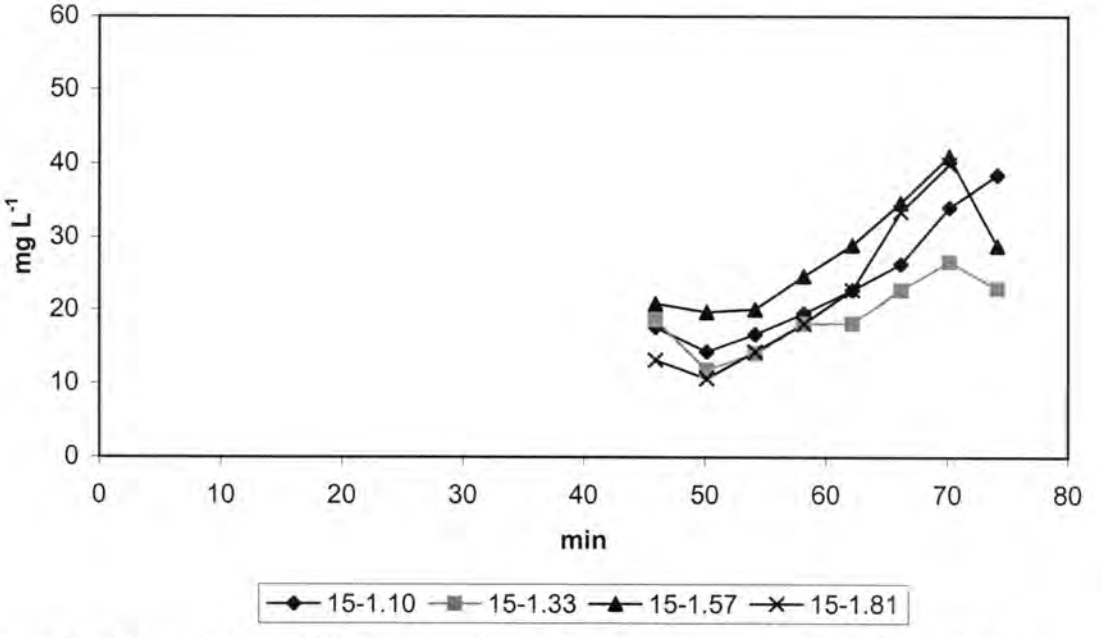

Figure 18. Concentration of Br in subsurface drainage versus time for 15% moisture

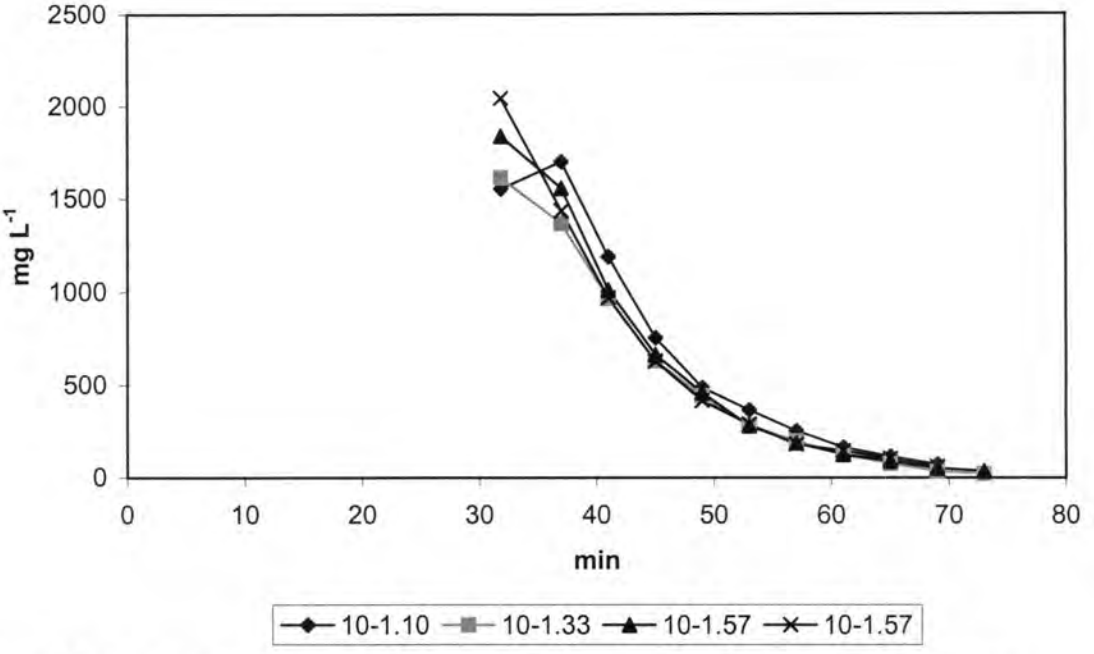

Figure 19. Concentration of Cl in subsurface drainage versus time for 10% moisture

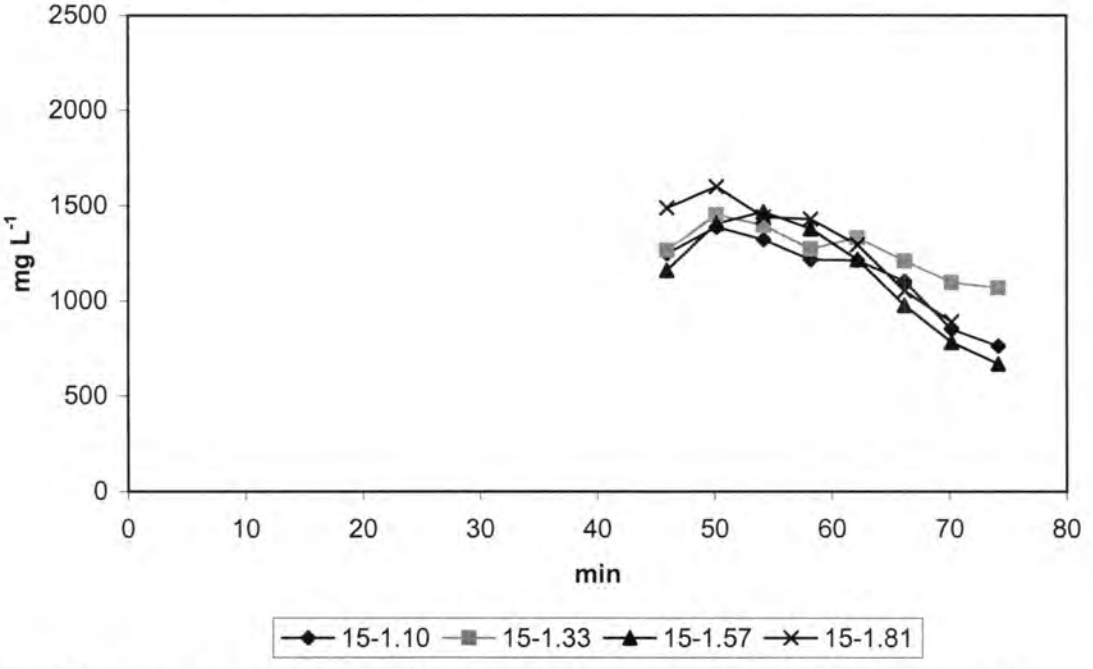

Figure 20. Concentration of Cl in subsurface drainage versus time for 15% moisture

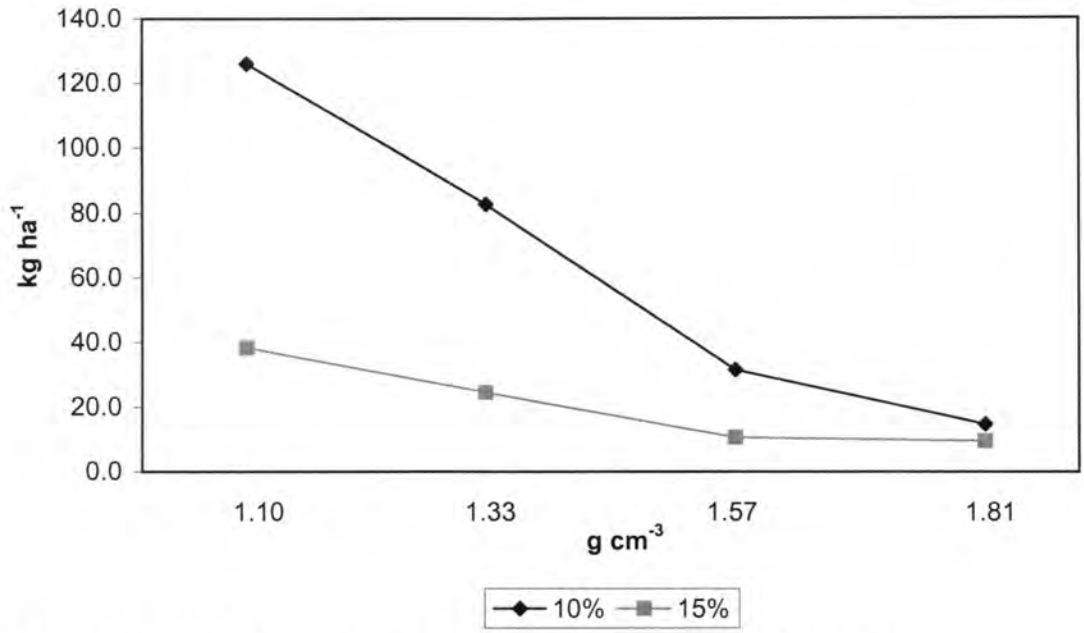

Figure 21. Interaction of bulk density with moisture content for NO_3-N loss in subsurface drainage

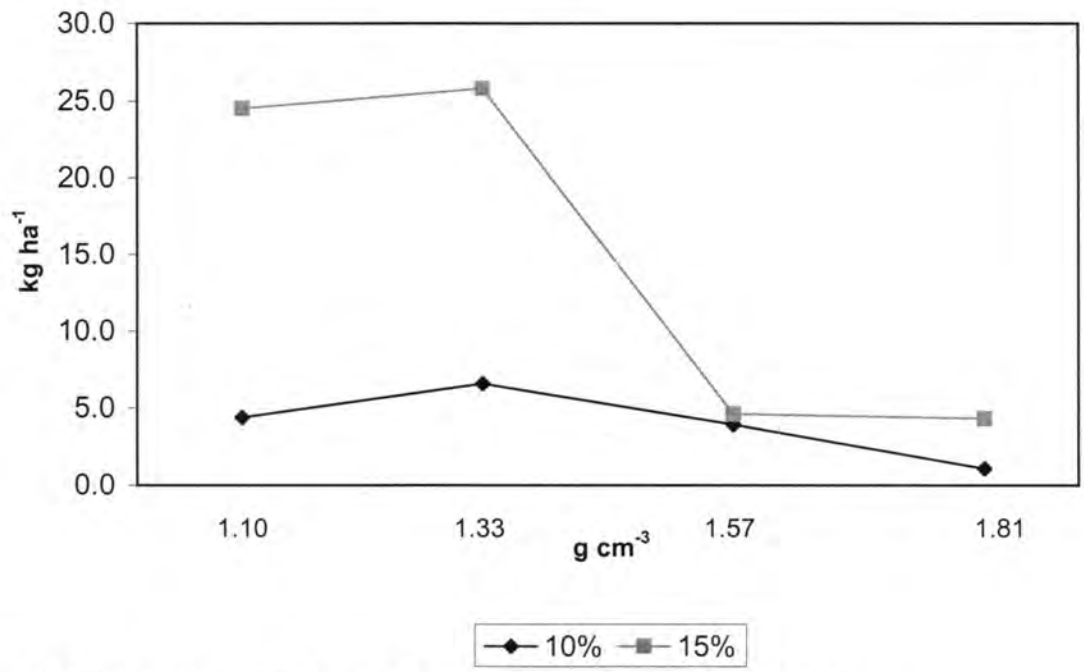

Figure 22. Interaction of bulk density with moisture content for NO_3-N retained by sand

Conclusions

Soil runoff pans with rainfall simulation were used to study the effect of two soil moisture contents, 10 and 15%, and four bulk densities, 1.10, 1.33, 1.57, 1.81 g cm^{-3} of soil bars on NO_3-N leaching from the zone of application. Bulk density treatments were put in the soil in the form of compacted soil bars at 3.8 cm (1.5 in) below the soil surface. Compacted soil bars represented only 3% of the soil surface area and at most 0.9% of the soil volume in the pan. Chloride was added with water to the soil prior to packing it in the pans. Rainfall with Br added to it was applied on 24 pans of soil.

The water mass balance indicated good tracking and recovery for all treatments. As expected, surface runoff began sooner for the 15% moisture content, resulting in greater runoff volumes. However, for subsurface hydrology the 15% soil moisture content had a longer time to the beginning of drainage and lesser drainage volumes. While the lower soil moisture content (10%) had a higher water holding capacity, the time to subsurface drainage was shorter and there were increased infiltration rate and greater volumes of subsurface drainage. This may be due to possibly differences in soil packing and greater surface sealing with rainfall energy of the unprotected surface soil at the higher initial moisture content. Due to the small percentage of the soil surface area and soil volume occupied by the compacted soil bars, bulk density showed no significant effect on surface and subsurface hydrology.

Surface runoff concentrations of NO_3-N and Br were not significantly affected by soil moisture content and bulk density. However, runoff losses of NO_3-N and Br were greater at the 15% moisture content because of greater runoff volumes. Chloride concentrations and losses in surface runoff were below the detectable limit.

Higher bulk density caused lower concentrations and losses of NO_3-N in subsurface drainage, resulting in a significant difference between bulk densities for both 10 and 15% moisture contents. The 10% moisture content produced greater NO_3-N losses due to greater volume of drainage at that moisture. NO_3-N mass balance indicated that higher bulk density and moisture content retained greater amounts of NO_3-N in soil and lesser amounts in sand. The interaction of moisture content with bulk density indicated that higher moisture content and bulk density reduced losses of NO_3-N into subsurface drainage.

Bromide concentrations and losses and Cl losses in subsurface drainage were lower at 15% moisture. However, Cl concentrations in subsurface drainage were lower at 10% moisture. Cl mass balance indicated greater storage of Cl in soil at higher moisture content. Br showed greater storage in soil at lower moisture content, and since Br was in the rainwater, it reflected similar trends of greater volumes of drainage at 10% moisture.

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CHAPTER 4. GENERAL CONCLUSIONS

Among all the agricultural chemicals that have the potential to contaminate groundwater, N applied as fertilizer and manure is the most extensively used, especially by corn producers. Current methods of fertilizer incorporation, either through tillage or through subsurface knife application, require tractive energy, and in addition, bury or destroy soil-protecting surface crop residue. Nitrate-nitrogen, because of its soluble and nonadsorbed nature, will readily move with water through the soil profile. One recent strategy to reduce NO_3-N leaching is to alter water flow in soil. By compacting the soil above applied N fertilizer combined with fertilizer placement away from zones of substantial vertical water movement should minimize NO_3-N leaching.

The overall objective of this research was to study the impacts of soil moisture content, soil bulk density, and simulated rainfall on the leaching characteristics of NO_3-N in subsurface drainage. This involved studying the compacted soil bars of four different bulk densities (1.10, 1.33, 1.57, 1.81 g cm^{-3}) with NO_3-N source applied to soil in pans at two moisture contents and that had been treated with Cl. Bulk density treatments were put in the soil in the form of compacted soil bars at 3.8 cm (1.5 in) below the soil surface. Compacted soil bars represented only 3% of the soil surface area and at most 0.9% of the soil volume in the pan. Rainfall with Br dissolved in it was applied at an indoor rainfall simulation facility and was simulated on 24 pans of soil.

Water mass balance indicated good tracking and recovery for all treatments. Two levels of moisture content had significant effects on surface and subsurface hydrology of the soil pans. As expected, surface runoff began sooner for the 15% moisture content, resulting in greater runoff volumes. However, surprisingly for subsurface hydrology, the 15% soil

moisture content had a longer time to the beginning of drainage and lesser drainage volumes. Due to the small percentage of the soil surface area and soil volume occupied by the compacted soil bars, bulk density showed no significant effect on surface and subsurface hydrology.

Surface runoff losses of NO_3-N and Br were greater at the 15% moisture content. Chloride concentrations and losses in runoff were below detectable limit.

Higher bulk density caused lower concentrations and losses of NO_3-N in the subsurface drainage, resulting in significant difference between bulk densities for both 10 and 15% moisture contents. Lower moisture content produced greater NO_3-N losses due to greater volume of subsurface drainage at that moisture content. Nitrate-nitrogen mass balance indicated that higher bulk density and moisture content stored greater amounts of NO_3-N in soil and lesser amounts in sand. The interaction of moisture content with bulk density indicated that higher moisture content and bulk density reduced losses of NO_3-N into subsurface drainage.

From the outcome of research results, it seems that compacting soil within the fertilizer application can minimize NO_3-N losses to subsurface drainage. Soil compaction to desired bulk density could be reached by adding or removing weights to the LCD applicator. LCD applicator can compact soil above the zone of N application, which can reflect similar results obtained in this research. Since higher soil moisture helped to reduce NO_3-N leaching, N fertilizer in liquid form can be used to bring the soil moisture to desired level.

Future research could involve examining compaction in the field and improving an N applicator. It will also be interesting to see different approach for moisture content treatments. Wetting soil to 10 and 15% moisture can be achieved after packing soil into pans.

However, this approach would add some complications in terms of uniformity of soil moisture content.

APPENDIX: RAINFALL SIMULATION DATA

Table 1. Runoff masses and concentrations of NO_3-N, Br, and Cl in runoff for 1.81 g/cm^3 bulk density and 10% moisture content.

		Rep 1					Rep 2					Rep 3			
Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L
29	373.2	0.139	48.472	ND*	23	470.2	0.013	48.253	ND	26	164.8	0.257	46.494	ND
31	251.7	0.139	48.472	ND	26	320.7	0.013	48.253	ND	28	189.6	0.257	46.494	ND
33	314.4	0.166	48.707	ND	28	362.2	0.000	48.613	ND	30	233.0	0.072	46.989	ND
35	399.5	0.166	48.707	ND	30	417.3	0.000	48.613	ND	32	367.1	0.072	46.989	ND
37	407.4	0.166	48.707	ND	32	478.0	0.000	48.613	ND	34	349.5	0.072	46.989	ND
39	400.4	0.166	48.707	ND	34	502.0	0.000	48.613	ND	36	365.1	0.072	46.989	ND
41	429.0	0.121	49.036	ND	36	489.9	0.019	49.032	ND	38	464.1	0.000	47.679	ND
43	441.0	0.121	49.036	ND	38	492.6	0.019	49.032	ND	40	415.1	0.000	47.679	ND
45	449.2	0.121	49.036	ND	40	496.1	0.019	49.032	ND	42	440.8	0.000	47.679	ND
47	470.1	0.121	49.036	ND	42	525.8	0.019	49.032	ND	44	471.6	0.000	47.679	ND
49	478.6	0.115	48.458	ND	44	537.3	0.000	48.850	ND	46	493.4	0.000	47.440	ND
51	490.3	0.115	48.458	ND	46	525.7	0.000	48.850	ND	48	482.7	0.000	47.440	ND
53	588.0	0.115	48.458	ND	48	553.1	0.000	48.850	ND	50	542.3	0.000	47.440	ND
55	520.1	0.115	48.458	ND	50	552.9	0.000	48.850	ND	52	484.8	0.000	47.440	ND
57	511.3	0.128	48.514	ND	52	540.2	0.000	48.688	ND	54	510.9	0.086	47.971	ND
59	506.1	0.128	48.514	ND	54	566.6	0.000	48.688	ND	56	492.0	0.086	47.971	ND
61	533.1	0.128	48.514	ND	56	572.8	0.000	48.688	ND	58	505.2	0.086	47.971	ND
63	535.1	0.128	48.514	ND	58	552.5	0.000	48.688	ND	60	527.0	0.086	47.971	ND
65	525.6	0.149	48.236	ND	60	590.0	0.000	49.104	ND	62	521.6	0.062	46.932	ND
67	573.3	0.149	48.236	ND	62	582.3	0.000	49.104	ND	64	534.6	0.062	46.932	ND
69	531.7	0.149	48.236	ND	64	559.4	0.000	49.104	ND	66	650.6	0.062	46.932	ND
70	470.7	0.149	48.236	ND	66	607.1	0.000	49.104	ND	68	550.4	0.062	46.932	ND
					68	589.1	0.000	48.723	ND	70	721.2	0.172	47.425	ND
					70	683.5	0.000	48.723	ND					

* ND = Not Detected

Table 2. Runoff masses and concentrations of NO_3-N, Br, and Cl in runoff for 1.81 g/cm^3 bulk density and 15% moisture content.

	Rep 1					Rep 2					Rep 3			
Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L
14	516.5	0.134	51.165	ND*	15	123.1	0.100	48.309	ND	9	281.9	0.164	50.375	ND
16	478.8	0.134	51.165	ND	17	261.8	0.100	48.309	ND	11	390.7	0.164	50.375	ND
18	476.6	0.020	50.620	ND	19	299.9	0.069	48.568	ND	13	498	0.106	50.238	ND
20	529.4	0.020	50.620	ND	21	374.2	0.069	48.568	ND	15	511.3	0.106	50.238	ND
22	531.8	0.020	50.620	ND	23	398.0	0.069	48.568	ND	17	532.1	0.106	50.238	ND
24	574.5	0.020	50.620	ND	25	421.4	0.069	48.568	ND	19	566.1	0.106	50.238	ND
26	578.1	0.070	50.896	ND	27	449.1	0.061	48.863	ND	21	550.2	0.078	50.090	ND
28	590.9	0.070	50.896	ND	29	456.0	0.061	48.863	ND	23	595.9	0.078	50.090	ND
30	612.2	0.070	50.896	ND	31	465.8	0.061	48.863	ND	25	580.5	0.078	50.090	ND
32	602.9	0.070	50.896	ND	33	492.6	0.061	48.863	ND	27	593.2	0.078	50.090	ND
34	626.4	0.000	51.238	ND	35	488.2	0.062	49.168	ND	29	581.4	0.026	49.919	ND
36	666.1	0.000	51.238	ND	37	507.0	0.062	49.168	ND	31	570.9	0.026	49.919	ND
38	654.2	0.000	51.238	ND	39	500.4	0.062	49.168	ND	33	599	0.026	49.919	ND
40	666.9	0.000	51.238	ND	41	537.2	0.062	49.168	ND	35	573.7	0.026	49.919	ND
42	739.8	0.087	51.582	ND	43	519.0	0.061	49.132	ND	37	598.5	0.100	50.073	ND
44	676.3	0.087	51.582	ND	45	539.2	0.061	49.132	ND	39	596.5	0.100	50.073	ND
46	709.8	0.087	51.582	ND	47	557.0	0.061	49.132	ND	41	613.3	0.100	50.073	ND
48	774.3	0.087	51.582	ND	49	549.3	0.061	49.132	ND	43	607	0.100	50.073	ND
50	691.1	0.070	51.095	ND	51	527.0	0.053	48.812	ND	45	617.6	0.111	50.967	ND
52	762.9	0.070	51.095	ND	53	538.0	0.053	48.812	ND	47	631.7	0.111	50.967	ND
54	739.1	0.070	51.095	ND	55	562.7	0.053	48.812	ND	49	641.9	0.111	50.967	ND
56	705.2	0.070	51.095	ND	57	572.4	0.053	48.812	ND	51	659.5	0.111	50.967	ND
58	801.2	0.120	51.759	ND	59	504.5	0.072	48.949	ND	53	671.8	0.114	51.013	ND
60	785.6	0.120	51.759	ND	61	574.7	0.072	48.949	ND	55	724.8	0.114	51.013	ND
62	686.6	0.120	51.759	ND	63	586.0	0.072	48.949	ND	57	686.9	0.114	51.013	ND
64	651.1	0.120	51.759	ND	65	591.3	0.072	48.949	ND	59	743.1	0.114	51.013	ND
66	658.2	0.085	52.460	ND	67	588.7	0.071	49.270	ND	61	746.7	0.120	51.809	ND
68	758.3	0.085	52.460	ND	69	600.0	0.071	49.270	ND	63	688.4	0.120	51.809	ND
70	755.9	0.085	52.460	ND	70	411.3	0.071	49.270	ND	65	688.5	0.120	51.809	ND
										67	707	0.120	51.809	ND
										69	716.2	0.056	51.052	ND
										70	457.9	0.056	51.052	ND

* ND = Not Detected

Table 3. Runoff masses and concentrations of NO_3-N, Br, and Cl in runoff for 1.57 g/cm^3 bulk density and 10% moisture content.

		Rep 1					Rep 2					Rep 3		
Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L
23	602.5	0.198	50.386	ND*	23	393.9	0.094	50.046	ND	28	331.4	0.187	47.404	ND
25	301.8	0.198	50.386	ND	26	239.9	0.094	50.046	ND	30	222.7	0.187	47.404	ND
27	337.4	0.008	51.323	ND	28	274	0.025	50.039	ND	32	374.2	0.066	47.364	ND
29	358.3	0.008	51.323	ND	30	320.4	0.025	50.039	ND	34	395.6	0.066	47.364	ND
31	324.5	0.008	51.323	ND	32	332.3	0.025	50.039	ND	36	400.4	0.066	47.364	ND
33	377.8	0.008	51.323	ND	34	386	0.025	50.039	ND	38	414.5	0.066	47.364	ND
35	464.2	0.042	51.335	ND	36	448.9	0.067	50.006	ND	40	439.3	0.027	47.705	ND
37	473	0.042	51.335	ND	38	444.5	0.067	50.006	ND	42	441.8	0.027	47.705	ND
39	475.6	0.042	51.335	ND	40	433.7	0.067	50.006	ND	44	451.7	0.027	47.705	ND
41	469.6	0.042	51.335	ND	42	470.4	0.067	50.006	ND	46	468.8	0.027	47.705	ND
43	486.2	0.000	51.255	ND	44	456.2	0.044	49.821	ND	48	465.1	0.108	47.924	ND
45	482.7	0.000	51.255	ND	46	463.3	0.044	49.821	ND	50	470.9	0.108	47.924	ND
47	486.1	0.000	51.255	ND	48	476.6	0.044	49.821	ND	52	479.6	0.108	47.924	ND
49	493.5	0.000	51.255	ND	50	495.4	0.044	49.821	ND	54	519.7	0.108	47.924	ND
51	487.9	0.000	51.541	ND	52	480.3	0.114	50.108	ND	56	489.4	0.159	49.033	ND
53	491.2	0.000	51.541	ND	54	492.8	0.114	50.108	ND	58	485.6	0.159	49.033	ND
55	499.4	0.000	51.541	ND	56	498.5	0.114	50.108	ND	60	420.9	0.159	49.033	ND
57	515.6	0.000	51.541	ND	58	495.3	0.114	50.108	ND	62	437.2	0.159	49.033	ND
59	516.3	0.000	52.455	ND	60	508.2	0.000	50.404	ND	64	419.9	0.140	49.198	ND
61	525.7	0.000	52.455	ND	62	524.3	0.000	50.404	ND	66	383.3	0.140	49.198	ND
63	565.5	0.000	52.455	ND	64	523.7	0.000	50.404	ND	68	406.6	0.140	49.198	ND
65	538.6	0.000	52.455	ND	66	562.6	0.000	50.404	ND	70	366.1	0.140	49.198	ND
67	554	0.000	52.300	ND	68	540	0.090	50.590	ND					
69	563.6	0.000	52.300	ND	70	522.9	0.090	50.590	ND					
70	400.4	0.000	52.300	ND										

* ND = Not Detected

Table 4. Runoff masses and concentrations of NO_3-N, Br, and Cl in runoff for 1.57 g/cm^3 bulk density and 15% moisture content.

		Rep 1					Rep 2					Rep 3			
Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L
15	242.4	0.127	48.940	ND*	11	323.4	0.263	49.306	ND	17	275.4	0.124	49.104	ND
17	342.2	0.127	48.940	ND	13	406.8	0.263	49.306	ND	19	303.9	0.124	49.104	ND
19	386.7	0.181	49.041	ND	15	457.4	0.100	48.298	ND	21	338.8	0.092	49.884	ND
21	430.6	0.181	49.041	ND	17	519.6	0.100	48.298	ND	23	401.4	0.092	49.884	ND
23	463.1	0.181	49.041	ND	19	513.6	0.100	48.298	ND	25	395.8	0.092	49.884	ND
25	472.3	0.181	49.041	ND	21	547.9	0.100	48.298	ND	27	421.6	0.092	49.884	ND
27	475.4	0.056	49.899	ND	23	573.9	0.088	48.213	ND	29	433.7	0.051	50.123	ND
29	501.7	0.056	49.899	ND	25	573.3	0.088	48.213	ND	31	440.1	0.051	50.123	ND
31	525.3	0.056	49.899	ND	27	577.4	0.088	48.213	ND	33	463.8	0.051	50.123	ND
33	550.4	0.056	49.899	ND	29	587.4	0.088	48.213	ND	35	455.2	0.051	50.123	ND
35	553.3	0.145	49.927	ND	31	574.4	0.067	48.834	ND	37	491.2	0.050	50.605	ND
37	551.1	0.145	49.927	ND	33	591.2	0.067	48.834	ND	39	503.0	0.050	50.605	ND
39	550.6	0.145	49.927	ND	35	597.5	0.067	48.834	ND	41	522.2	0.050	50.605	ND
41	556.5	0.145	49.927	ND	37	592.2	0.067	48.834	ND	43	522.8	0.050	50.605	ND
43	565.1	0.060	50.206	ND	39	598.1	0.071	49.542	ND	45	536.9	0.112	51.342	ND
45	548.7	0.060	50.206	ND	41	615.6	0.071	49.542	ND	47	547.8	0.112	51.342	ND
47	571.7	0.060	50.206	ND	43	593.4	0.071	49.542	ND	49	568.6	0.112	51.342	ND
49	587.7	0.060	50.206	ND	45	612.0	0.071	49.542	ND	51	552.9	0.112	51.342	ND
51	812.0	0.158	47.735	ND	47	628.4	0.055	48.905	ND	53	571.7	0.108	51.472	ND
53	676.4	0.158	47.735	ND	49	626.8	0.055	48.905	ND	55	595.4	0.108	51.472	ND
55	618.1	0.158	47.735	ND	51	635.5	0.055	48.905	ND	57	555.3	0.108	51.472	ND
57	727.5	0.158	47.735	ND	53	662.4	0.055	48.905	ND	59	603.9	0.108	51.472	ND
59	678.0	0.399	50.752	ND	55	674.7	0.140	48.823	ND	61	600.7	0.103	51.063	ND
61	644.3	0.399	50.752	ND	57	669.2	0.140	48.823	ND	63	570.7	0.103	51.063	ND
63	656.1	0.399	50.752	ND	59	677.8	0.140	48.823	ND	65	566.8	0.103	51.063	ND
64	302.6	0.399	50.752	ND	61	685.1	0.140	48.823	ND	67	590.3	0.103	51.063	ND
66	664.9	0.106	48.969	ND	63	708.9	0.070	48.899	ND	69	599.2	0.053	51.006	ND
68	604.2	0.106	48.969	ND	65	723.7	0.070	48.899	ND	70	382.9	0.053	51.006	ND
70	674.8	0.106	48.969	ND	67	707.7	0.070	48.899	ND					
					69	726.6	0.070	48.899	ND					
					70	503.0	0.077	49.073	ND					

* ND = Not Detected

Table 5. Runoff masses and concentrations of NO_3-N, Br, and Cl in runoff for 1.33 g/cm^3 bulk density and 10% moisture content.

	Rep 1					Rep 2					Rep 3			
Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L
23	545.6	0.018	51.150	ND*	28	284.4	0.000	49.064	ND	28	439.0	0.217	49.839	ND
25	297.8	0.018	51.150	ND	30	252.9	0.000	49.064	ND	30	377.4	0.217	49.839	ND
27	330.9	0.000	51.393	ND	32	350.3	0.025	49.808	ND	32	415.5	0.170	49.707	ND
29	363	0.000	51.393	ND	34	371.0	0.025	49.808	ND	34	418.5	0.170	49.707	ND
31	373.1	0.000	51.393	ND	36	380.8	0.025	49.808	ND	36	422.0	0.170	49.707	ND
33	377.7	0.000	51.393	ND	38	403.4	0.025	49.808	ND	38	442.7	0.170	49.707	ND
35	401.6	0.167	50.634	ND	40	407.5	0.121	49.729	ND	40	467.4	0.102	51.020	ND
37	426.3	0.167	50.634	ND	42	431.3	0.121	49.729	ND	42	494.8	0.102	51.020	ND
39	465.8	0.167	50.634	ND	44	431.0	0.121	49.729	ND	44	497.2	0.102	51.020	ND
41	474.5	0.167	50.634	ND	46	431.8	0.121	49.729	ND	46	527.7	0.102	51.020	ND
43	474.4	0.100	50.366	ND	48	446.0	0.017	49.778	ND	48	530.8	0.162	50.547	ND
45	477.3	0.100	50.366	ND	50	452.8	0.017	49.778	ND	50	527.1	0.162	50.547	ND
47	477.7	0.100	50.366	ND	52	470.5	0.017	49.778	ND	52	558.1	0.162	50.547	ND
49	481.6	0.100	50.366	ND	54	464.7	0.017	49.778	ND	54	566.4	0.162	50.547	ND
51	486.5	0.000	51.064	ND	56	527.9	0.137	50.389	ND	56	545.1	0.177	51.631	ND
53	474.7	0.000	51.064	ND	58	528.6	0.137	50.389	ND	58	548.7	0.177	51.631	ND
55	495.6	0.000	51.064	ND	60	518.6	0.137	50.389	ND	60	458.5	0.177	51.631	ND
57	501.3	0.000	51.064	ND	62	498.4	0.137	50.389	ND	62	484.0	0.177	51.631	ND
59	499.3	0.000	51.306	ND	64	519.4	0.187	50.806	ND	64	463.2	0.088	51.634	ND
61	503.6	0.000	51.306	ND	66	622.5	0.187	50.806	ND	66	399.6	0.088	51.634	ND
63	545.3	0.000	51.306	ND	68	528.4	0.187	50.806	ND	68	425.7	0.088	51.634	ND
65	524.8	0.000	51.306	ND	70	631.0	0.187	50.806	ND	70	420.5	0.088	51.634	ND
67	534.9	0.152	51.999	ND										
69	556.1	0.152	51.999	ND										
70	372.6	0.152	51.999	ND										

* ND = Not Detected

Table 6. Runoff masses and concentrations of NO_3-N, Br, and Cl in runoff for 1.33 g/cm^3 bulk density and 15% moisture content.

		Rep 1					Rep 2					Rep 3			
Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L
14	280.3	0.083	51.767	ND*	12	240.0	0.211	47.946	ND	16	423.7	0.125	51.036	ND
16	400.4	0.083	51.767	ND	14	316.3	0.211	47.946	ND	18	358.4	0.125	51.036	ND
18	416.4	0.028	51.237	ND	16	391.8	0.110	47.909	ND	20	410.1	0.104	50.615	ND
20	468.9	0.028	51.237	ND	18	429.6	0.110	47.909	ND	22	429.7	0.104	50.615	ND
22	474.0	0.028	51.237	ND	20	469.8	0.110	47.909	ND	24	451.0	0.104	50.615	ND
24	518.3	0.028	51.237	ND	22	483.2	0.110	47.909	ND	26	463.9	0.104	50.615	ND
26	525.7	0.047	52.748	ND	24	523.2	0.092	48.697	ND	28	487.5	0.110	51.375	ND
28	545.2	0.047	52.748	ND	26	516.3	0.092	48.697	ND	30	502.4	0.110	51.375	ND
30	551.0	0.047	52.748	ND	28	555.8	0.092	48.697	ND	32	505.7	0.110	51.375	ND
32	545.8	0.047	52.748	ND	30	599.9	0.092	48.697	ND	34	496.9	0.110	51.375	ND
34	574.6	0.025	52.877	ND	32	524.4	0.102	49.443	ND	36	517.6	0.127	52.286	ND
36	617.0	0.025	52.877	ND	34	562.6	0.102	49.443	ND	38	523.8	0.127	52.286	ND
38	592.0	0.025	52.877	ND	36	593.2	0.102	49.443	ND	40	525.8	0.127	52.286	ND
40	607.8	0.025	52.877	ND	38	574.8	0.102	49.443	ND	42	530.3	0.127	52.286	ND
42	668.4	0.067	52.252	ND	40	587.4	0.088	48.702	ND	44	530.2	0.164	52.959	ND
44	619.8	0.067	52.252	ND	42	592.0	0.088	48.702	ND	46	533.1	0.164	52.959	ND
46	651.2	0.067	52.252	ND	44	681.4	0.088	48.702	ND	48	546.0	0.164	52.959	ND
48	699.2	0.067	52.252	ND	46	631.7	0.088	48.702	ND	50	580.3	0.164	52.959	ND
50	628.5	0.079	52.575	ND	48	683.7	0.096	49.290	ND	52	556.1	0.104	53.163	ND
52	686.8	0.079	52.575	ND	50	583.9	0.096	49.290	ND	54	553.9	0.104	53.163	ND
54	674.2	0.079	52.575	ND	52	615.2	0.096	49.290	ND	56	546.8	0.104	53.163	ND
56	628.6	0.079	52.575	ND	54	641.7	0.096	49.290	ND	58	546.1	0.104	53.163	ND
58	712.6	0.000	52.126	ND	56	660.2	0.138	48.645	ND	60	586.1	0.132	53.049	ND
60	694.9	0.000	52.126	ND	58	672.0	0.138	48.645	ND	62	569.6	0.132	53.049	ND
62	618.3	0.000	52.126	ND	60	683.9	0.138	48.645	ND	64	624.0	0.132	53.049	ND
64	584.2	0.000	52.126	ND	62	722.2	0.138	48.645	ND	66	595.0	0.132	53.049	ND
66	578.8	0.115	52.550	ND	64	718.7	0.138	48.659	ND	68	586.1	0.138	52.993	ND
68	675.8	0.115	52.550	ND	66	721.1	0.138	48.659	ND	70	665.4	0.138	52.993	ND
70	626.5	0.115	52.550	ND	68	738.8	0.138	48.659	ND					
					70	819.9	0.138	48.659	ND					

* ND = Not Detected

Table 7. Runoff masses and concentrations of NO_3-N, Br, and Cl in runoff for 1.10 g/cm^3 bulk density and 10% moisture content.

Rep 1					Rep 2					Rep 3				
Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L
29	223.6	0.2731	50.1542	ND*	24	442.9	0.2039	49.7464	ND	23	355.7	1.1146	48.3588	ND
31	188.7	0.2731	50.1542	ND	26	303.2	0.2039	49.7464	ND	26	418.9	1.1146	48.3588	ND
33	224.7	0.1707	49.7170	ND	28	353.2	0.1948	49.7226	ND	28	312.5	0.1516	48.9596	ND
35	265.4	0.1707	49.7170	ND	30	434.1	0.1948	49.7226	ND	30	326.1	0.1516	48.9596	ND
37	349.3	0.1707	49.7170	ND	32	484.8	0.1948	49.7226	ND	32	385.6	0.1516	48.9596	ND
39	361.6	0.1707	49.7170	ND	34	490.5	0.1948	49.7226	ND	34	410.5	0.1516	48.9596	ND
41	402.5	0.1461	50.1516	ND	36	503.4	0.0000	49.8518	ND	36	351	0.0394	48.8918	ND
43	423.8	0.1461	50.1516	ND	38	522.8	0.0000	49.8518	ND	38	531.1	0.0394	48.8918	ND
45	442.4	0.1461	50.1516	ND	40	510.1	0.0000	49.8518	ND	40	472.4	0.0394	48.8918	ND
47	454.6	0.1461	50.1516	ND	42	538.9	0.0000	49.8518	ND	42	490.8	0.0394	48.8918	ND
49	466.2	0.1390	50.2241	ND	44	531.2	0.2305	50.1522	ND	44	507.2	0.2109	48.8530	ND
51	491.5	0.1390	50.2241	ND	46	522.6	0.2305	50.1522	ND	46	553.6	0.2109	48.8530	ND
53	559.7	0.1390	50.2241	ND	48	520.3	0.2305	50.1522	ND	48	541.3	0.2109	48.8530	ND
55	515.3	0.1390	50.2241	ND	50	542.9	0.2305	50.1522	ND	50	616.6	0.2109	48.8530	ND
57	505	0.0530	50.1173	ND	52	552	0.0000	49.7457	ND	52	542.6	0.0446	49.4056	ND
59	498.8	0.0530	50.1173	ND	54	539.3	0.0000	49.7457	ND	54	585.4	0.0446	49.4056	ND
61	522	0.0530	50.1173	ND	56	577.7	0.0000	49.7457	ND	56	564	0.0446	49.4056	ND
63	508.5	0.0530	50.1173	ND	58	582.2	0.0000	49.7457	ND	58	579.9	0.0446	49.4056	ND
65	496.8	0.1283	50.4015	ND	60	607	0.0385	50.2555	ND	60	604	0.0528	49.5258	ND
67	536.6	0.1283	50.4015	ND	62	604.8	0.0385	50.2555	ND	62	583.5	0.0528	49.5258	ND
69	504.4	0.1283	50.4015	ND	64	622	0.0385	50.2555	ND	64	608.6	0.0528	49.5258	ND
70	448.2	0.1283	50.4015	ND	66	575.1	0.0385	50.2555	ND	66	769.3	0.0528	49.5258	ND
					68	647.8	0.1521	49.9995	ND	68	633.8	0.0253	49.6237	ND
					70	746.6	0.1521	49.9995	ND	70	864.3	0.0253	49.6237	ND

* ND = Not Detected

Table 8. Runoff masses and concentrations of NO_3-N, Br, and Cl in runoff for 1.10 g/cm^3 bulk density and 15% moisture content.

		Rep 1					Rep 2					Rep 3			
Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Runoff mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L
15	636.0	0.195	48.683	ND*	16	364.9	0.247	48.337	ND	12	242.0	0.178	51.401	ND
17	426.8	0.195	48.683	ND	18	312.8	0.247	48.337	ND	14	352.5	0.178	51.401	ND
19	459.5	0.192	47.345	ND	20	377.6	0.099	47.768	ND	16	479.9	0.140	51.387	ND
21	510.8	0.192	47.345	ND	22	403.7	0.099	47.768	ND	18	486.9	0.140	51.387	ND
23	536.8	0.192	47.345	ND	24	445.9	0.099	47.768	ND	20	524.1	0.140	51.387	ND
25	544.4	0.192	47.345	ND	26	455.4	0.099	47.768	ND	22	534.7	0.140	51.387	ND
27	558.2	0.101	47.985	ND	28	487.4	0.090	48.603	ND	24	548.9	0.091	50.959	ND
29	587.6	0.101	47.985	ND	30	520.2	0.090	48.603	ND	26	551.6	0.091	50.959	ND
31	594.6	0.101	47.985	ND	32	468.7	0.090	48.603	ND	28	567.3	0.091	50.959	ND
33	617.3	0.101	47.985	ND	34	513.1	0.090	48.603	ND	30	578.7	0.091	50.959	ND
35	623.4	0.121	49.260	ND	36	526.4	0.064	49.157	ND	32	565.4	0.088	51.829	ND
37	605.7	0.121	49.260	ND	38	528.0	0.064	49.157	ND	34	568.1	0.088	51.829	ND
39	612.0	0.121	49.260	ND	40	535.7	0.064	49.157	ND	36	588.6	0.088	51.829	ND
41	627.4	0.121	49.260	ND	42	553.4	0.064	49.157	ND	38	581.7	0.088	51.829	ND
43	651.3	0.115	48.769	ND	44	628.2	0.063	49.163	ND	40	584.6	0.115	51.897	ND
45	611.9	0.115	48.769	ND	46	580.1	0.063	49.163	ND	42	603.5	0.115	51.897	ND
47	636.9	0.115	48.769	ND	48	635.2	0.063	49.163	ND	44	600.2	0.115	51.897	ND
49	659.5	0.115	48.769	ND	50	554.1	0.063	49.163	ND	46	594.2	0.115	51.897	ND
51	892.6	0.126	49.314	ND	52	569.0	0.066	49.322	ND	48	616.8	0.064	52.925	ND
53	749.0	0.126	49.314	ND	54	583.2	0.066	49.322	ND	50	644.6	0.064	52.925	ND
55	693.0	0.126	49.314	ND	56	581.8	0.066	49.322	ND	52	612.2	0.064	52.925	ND
57	803.2	0.126	49.314	ND	58	595.5	0.066	49.322	ND	54	638.2	0.064	52.925	ND
59	751.4	0.112	50.154	ND	60	615.7	0.083	49.815	ND	56	630.6	0.122	52.638	ND
61	721.0	0.112	50.154	ND	62	651.4	0.083	49.815	ND	58	634.2	0.122	52.638	ND
63	730.5	0.112	50.154	ND	64	626.8	0.083	49.815	ND	60	663.4	0.122	52.638	ND
64	332.1	0.112	50.154	ND	66	626.5	0.083	49.815	ND	62	645.7	0.122	52.638	ND
66	751.3	0.123	48.395	ND	68	663.1	0.080	49.271	ND	64	718.2	0.145	52.052	ND
68	668.3	0.123	48.395	ND	70	731.4	0.080	49.271	ND	66	688.5	0.145	52.052	ND
70	743.8	0.123	48.395	ND						68	681.0	0.145	52.052	ND
										70	753.8	0.145	52.052	ND

* ND = Not Detected

Table 9. Subsurface drainage masses and concentrations of NO_3-N, Br, and Cl in subsurface for 1.81 g/cm^3 bulk density and 10% moisture content.

Rep 1					Rep 2					Rep 3				
Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L
36	600.8	183.863	28.575	2052.476	37	727.4	213.890	30.300	2108.460	35	708.6	219.382	31.613	1974.778
40	624.9	143.344	40.574	1459.706	41	785.0	162.020	45.348	1367.024	39	603.1	164.636	43.032	1482.060
44	624.6	103.587	49.600	996.030	45	510.6	109.914	55.160	914.885	43	513.6	118.032	47.561	997.013
48	598.9	76.200	50.763	628.822	49	506.9	91.085	58.416	536.768	47	544.4	92.227	49.602	722.277
52	411.6	61.129	53.620	420.402	53	485.6	65.475	58.508	345.073	51	507.9	64.514	50.500	484.392
56	422.2	40.233	52.884	306.416	57	477.6	55.619	57.577	257.777	55	510.4	51.340	49.152	303.471
60	436.9	46.641	51.858	207.708	61	474.7	54.810	56.291	139.779	59	493.5	38.021	49.423	196.915
64	439.5	40.918	51.254	151.650	65	456.7	49.501	54.272	96.885	63	468.4	32.526	49.023	191.475
68	437.1	39.066	51.509	115.332	69	450.5	46.551	52.800	63.046	67	452.0	25.955	46.986	130.969
74	509.5	38.107	49.846	73.397	73	428.9	50.489	51.406	38.782	73	543.0	27.692	47.173	69.383

Table 10. Subsurface drainage masses and concentrations of NO_3-N, Br, and Cl in subsurface for 1.81 g/cm^3 bulk density and 15% moisture content.

Rep 1					Rep 2					Rep 3				
Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L
45	283.9	182.995	3.905	1783.147	48	319.7	203.243	17.499	1468.003	58	210.5	150.935	18.190	1213.255
49	299.5	186.876	5.931	1567.472	52	439.8	206.962	15.023	1689.180	62	171.5	172.701	11.072	1540.807
53	280.4	175.797	9.689	1511.517	56	315.7	186.873	22.595	1350.794	66	169.6	175.399	10.603	1465.380
57	273.3	165.689	14.463	1398.317	60	364.2	166.832	28.487	1296.585	70	189.7	171.505	11.445	1595.375
61	280.5	178.115	19.603	1310.795	64	339.2	158.521	35.266	1054.443	74	181.4	172.198	13.461	1519.246
65	278.5	152.944	26.239	1185.277	68	309.0	142.929	40.786	921.925					
72	462.1	147.525	34.481	991.164	72	302.6	119.785	45.436	791.284					

Table 11. Subsurface drainage masses and concentrations of NO_3-N, Br, and Cl in subsurface for 1.57 g/cm^3 bulk density and 10% moisture content.

Rep 1					Rep 2					Rep 3				
Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L
38	801.0	127.377	42.837	2186.851	37	649.5	165.516	36.651	1845.938	31	472.0	158.199	35.051	1484.869
42	539.7	188.015	41.300	1544.169	41	506.5	161.436	44.089	1450.807	35	648.4	190.616	36.651	1682.995
46	486.6	188.988	48.054	966.473	45	536.6	122.371	51.811	948.135	39	615.9	137.136	47.022	1122.705
50	471.8	249.772	53.566	640.743	49	537.3	95.773	55.028	662.322	43	616.1	110.244	52.360	694.417
54	467.0	342.138	57.430	471.251	53	521.5	84.094	57.213	451.290	47	595.3	88.985	53.642	460.956
58	446.1	467.365	66.853	265.574	57	508.4	83.349	56.715	251.393	51	548.5	71.107	53.101	327.252
62	441.8	579.445	57.829	190.266	61	494.0	91.618	54.536	182.623	55	543.2	68.366	51.795	190.120
68	629.5	657.041	55.852	125.895	65	486.4	105.612	52.221	137.988	59	534.8	65.895	51.356	115.644
75	620.1	680.082	53.623	83.022	69	500.3	114.144	51.020	93.383	63	515.8	71.045	49.440	93.935
					73	445.4	133.943	52.493	43.586	67	471.4	69.477	48.539	59.788
										73	613.5	74.200	47.783	36.559

Table 12. Subsurface drainage masses and concentrations of NO_3-N, Br, and Cl in subsurface for 1.57 g/cm^3 bulk density and 15% moisture content.

Rep 1					Rep 2					Rep 3				
Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L
46	432.1	168.765	17.734	1433.214	48	155.0	47.044	25.272	298.504	46	184.4	219.446	19.707	1749.675
50	295.3	172.947	21.717	1459.972	52	169.6	146.903	25.186	995.196	50	248.6	204.986	12.261	1764.162
54	296.2	171.839	26.062	1305.222	56	258.7	178.381	15.982	1349.531	54	432.9	204.423	18.206	1749.558
58	291.9	153.322	30.516	1272.922	60	259.3	166.615	15.091	1398.027	58	434.3	190.229	28.438	1467.504
62	293.6	147.796	34.852	1074.592	64	254.5	168.275	15.322	1356.480	62	355.5	167.323	36.603	1222.661
66	272.4	138.371	38.136	965.508	68	305.8	139.347	22.184	1005.427	66	312.8	149.966	44.001	962.874
69	219.3	125.641	41.763	951.184	72	351.1	108.149	32.143	715.997	70	371.6	121.429	49.136	683.192
72	213.6	118.043	4.700	884.654						74	303.2	96.658	53.000	455.149

Table 13. Subsurface drainage masses and concentrations of NO_3-N, Br, and Cl in subsurface for 1.33 g/cm^3 bulk density and 10% moisture content.

Rep 1					Rep 2					Rep 3				
Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L
38	383.5	212.421	29.106	1098.881	33	750.2	451.018	28.816	1754.199	31	730.4	316.619	27.457	1989.776
42	524.6	169.206	46.143	1464.191	37	722.0	625.004	38.979	1495.313	35	755.0	443.167	43.076	1142.762
46	521.0	130.921	54.663	1236.649	41	653.3	731.875	49.294	916.027	39	699.4	608.103	50.284	745.446
50	495.3	124.703	58.656	887.954	45	614.9	795.565	53.419	553.919	43	659.8	697.176	52.766	450.075
54	508.9	129.284	59.772	748.154	49	556.8	715.136	54.882	321.006	47	632.5	675.563	53.220	260.470
58	489.5	138.703	59.069	445.996	53	541.4	677.906	54.694	256.695	51	588.8	706.580	52.535	153.199
62	485.8	157.728	57.727	364.965	57	530.9	607.182	53.431	137.132	55	591.9	597.522	51.311	96.998
68	727.3	182.555	55.242	214.170	61	414.7	587.906	52.375	94.788	59	569.6	536.861	49.066	56.843
75	683.1	208.225	52.942	117.368	65	457.3	487.144	51.713	65.381	63	544.1	514.631	47.600	44.161
					73	852.1	390.473	51.057	35.657	67	524.3	444.037	47.525	33.861
										73	720.7	345.707	47.037	20.661

Table 14. Subsurface drainage masses and concentrations of NO_3-N, Br, and Cl in subsurface for 1.33 g/cm^3 bulk density and 15% moisture content.

Rep 1					Rep 2					Rep 3				
Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L
45	276.2	142.856	16.709	1245.815	45	378.6	461.527	27.689	932.050	53	254.8	295.437	11.580	1622.378
49	254.3	218.776	5.160	1629.579	49	264.4	400.840	20.349	1110.642	57	297.1	314.804	9.951	1619.104
53	259.4	215.802	10.279	1515.206	53	212.4	466.613	18.966	1102.353	61	287.9	372.684	13.099	1578.859
57	254.0	315.606	11.271	1454.301	57	83.1	539.443	27.525	854.805	65	293.3	426.266	15.677	1510.432
61	264.2	304.581	16.691	1395.608	61	314.2	439.111	17.529	1155.932	69	267.9	568.888	20.331	1445.097
65	263.5	406.073	22.575	1280.074	65	58.3	485.909	19.447	1111.907	74	305.0	755.600	26.272	1239.548
72	479.0	528.155	32.292	1092.370	69	335.6	631.622	21.038	1100.181					
					72	210.0	736.511	22.986	1070.825					

Table 15. Subsurface drainage masses and concentrations of NO_3-N, Br, and Cl in subsurface for 1.10 g/cm^3 bulk density and 10% moisture content.

Rep 1					Rep 2					Rep 3				
Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L
36	442.2	274.419	35.922	1267.581	33	843.3	481.070	33.796	1604.158	35	461.1	474.715	33.627	1791.445
40	551.4	550.045	34.823	1827.566	37	668.7	1179.684	41.695	1632.576	39	629.5	925.767	41.567	1642.872
44	541.2	894.163	43.124	1381.341	41	631.8	1267.333	50.491	1018.685	43	607.5	1400.459	50.654	1169.393
48	530.3	1144.338	49.296	998.789	45	620.5	1141.932	55.463	547.448	47	576.6	1304.555	55.746	721.145
52	422.1	1155.677	52.832	720.009	49	578.8	913.850	55.056	356.276	51	552.3	1135.986	56.290	388.565
56	392.7	1267.167	54.687	576.248	53	569.9	634.622	53.519	247.349	55	538.1	882.955	55.450	275.583
60	422.5	988.176	55.097	448.494	57	579.1	442.368	52.611	154.073	59	524.8	717.691	54.771	161.555
64	419.2	776.198	56.726	312.559	61	519	318.379	54.733	78.525	63	528.1	381.288	52.343	103.087
68	426.1	638.512	54.063	223.716	65	576.6	230.960	51.868	48.243	67	522.8	284.721	51.406	72.269
74	471.7	512.210	53.509	145.360	73	910.2	147.263	51.373	33.354	73	627.1	183.990	49.998	40.054

Table 16. Subsurface drainage masses and concentrations of NO_3-N, Br, and Cl in subsurface for 1.10 g/cm^3 bulk density and 15% moisture content.

Rep 1					Rep 2					Rep 3				
Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L	Collection Time min	Drainage Mass g	NO3-N conc mg/L	Br conc mg/L	Cl conc mg/L
46	528.7	177.299	14.159	1282.973	45	283.7	442.555	16.324	1450.789	53	214.1	126.558	22.570	1008.770
50	358.7	194.272	20.205	1122.157	49	269.7	689.466	10.324	1664.747	57	208.4	204.310	12.373	1379.283
54	387.2	229.705	24.351	998.349	53	286.2	825.934	12.584	1584.955	61	232.4	237.669	13.208	1382.528
58	385.3	280.767	28.328	906.415	57	310.5	997.320	16.904	1365.636	65	258.0	273.594	13.335	1375.397
62	396.7	352.986	31.365	827.396	61	262.2	1299.640	21.447	1378.409	69	278.1	330.804	15.501	1434.415
66	410.1	462.127	34.254	687.360	65	285.1	1396.677	26.466	1361.926	74	300.3	402.715	18.254	1259.606
69	345.2	556.585	36.296	612.675	69	257.2	1492.479	31.970	1090.279					
72	316.5	706.101	40.735	584.542	72	188.0	1507.391	36.301	943.077					

Table 17. Times to beginnings of runoff and subsurface drainage

Moisture content %	Bulk density g/cm^3	Replication	Runoff start time min	Subsurface drainage start time min
10	1.81	1	25	30
		2	20	27
		3	23	29
10	1.57	1	20	32
		2	20	27
		3	23	27
10	1.33	1	19	32
		2	24	27
		3	23	27
10	1.10	1	26	30
		2	19	27
		3	20	29
15	1.81	1	11	42
		2	13	41
		3	7	52
15	1.57	1	13	40
		2	9	47
		3	14	39
15	1.33	1	11	42
		2	10	42
		3	13	49
15	1.10	1	11	40
		2	13	41
		3	10	49

Table 18. Water mass balance for 4 bulk densities and 2 moisture contents

Moisture Content %	Bulk Density g/cm^3	Replication	Rainfall Quantity cm	Subsurface Drainage cm	Runoff Quantity cm	Stored Quantity cm	Collected Quantity cm	Difference cm
10	1.81	1	7.13	1.56	3.11	3.08	7.75	-0.62
		2	7.59	1.62	3.83	2.81	8.26	-0.67
		3	7.96	1.63	3.19	2.91	7.73	0.23
10	1.57	1	7.41	1.49	3.59	2.74	7.83	-0.42
		2	7.59	1.58	3.29	2.89	7.75	-0.17
		3	7.72	1.88	2.83	2.98	7.7	0.02
10	1.33	1	7.41	1.47	3.49	2.94	7.91	-0.49
		2	7.78	1.86	3.03	2.8	7.69	0.09
		3	7.72	2.14	3.18	2.83	8.15	-0.43
10	1.1	1	7.13	1.41	2.86	3.16	7.43	-0.3
		2	7.78	1.98	3.89	2.92	8.78	-1
		3	7.96	1.7	3.84	3.08	8.62	-0.66
15	1.81	1	8.14	0.66	5.79	2.08	8.52	-0.39
		2	7.75	0.73	4.27	2.4	7.4	0.35
		3	7.93	0.28	5.86	1.97	8.11	-0.18
15	1.57	1	8.07	0.71	4.86	2.23	7.8	0.28
		2	7.75	0.53	5.63	2.12	8.28	-0.54
		3	7.93	0.81	4.21	2.56	7.57	0.36
15	1.33	1	8.14	0.62	5.14	2.16	7.92	0.21
		2	7.82	0.57	5.34	2.22	8.13	-0.31
		3	7.49	0.52	4.46	2.21	7.19	0.3
15	1.1	1	8.07	0.95	5.59	2.17	8.71	-0.64
		2	7.82	0.65	4.61	2.32	7.59	0.24
		3	7.49	0.45	5.33	2.12	7.91	-0.41

Table 19. NO_3-N mass balance

Moisture Content	Bulk Density	Rep	Runoff	Retained by Soil	Retained by Sand	Sub-Surface Drainage	Total started	Total recovered	Difference
%	g/cm^3		kg/ha						
	1.81	1	0.04	92.97	1.44	13.03	118.68	107.48	9.43
10		2	0.00	85.04	1.17	16.30	119.60	102.51	14.30
		3	0.02	69.63	0.66	14.79	114.05	85.10	25.38
	1.57	1	0.01	58.10	5.27	57.08	119.84	120.46	-0.52
10		2	0.02	87.44	4.52	18.47	119.60	110.45	7.65
		3	0.03	87.89	2.02	19.20	113.82	109.14	4.11
	1.33	1	0.02	57.17	5.31	23.94	119.84	86.45	27.87
10		2	0.03	2.48	8.13	111.06	117.88	121.69	-3.23
		3	0.05	8.34	6.34	113.26	113.82	127.98	-12.44
	1.10	1	0.04	6.14	8.97	114.52	118.68	129.67	-9.26
10		2	0.04	0.44	1.88	130.54	117.88	132.90	-12.74
		3	0.06	2.28	2.38	132.56	114.05	137.29	-20.37
	1.81	1	0.04	97.64	2.86	11.07	118.63	111.61	5.92
15		2	0.03	99.82	2.48	12.49	129.56	114.81	11.38
		3	0.06	97.00	7.70	4.72	128.61	109.48	14.87
	1.57	1	0.08	96.83	3.07	10.77	118.51	110.76	6.54
15		2	0.05	104.46	6.46	7.47	129.56	118.44	8.58
		3	0.04	91.01	4.36	13.51	128.61	108.93	15.30
	1.33	1	0.03	68.73	22.29	20.47	118.63	111.53	5.99
15		2	0.06	63.63	25.36	29.19	128.74	118.23	8.16
		3	0.06	53.15	29.75	23.89	128.82	106.85	17.06
	1.10	1	0.07	52.88	25.87	33.70	118.51	112.53	5.04
15		2	0.04	24.40	27.42	69.00	128.74	120.85	6.13
		3	0.06	74.77	20.22	12.45	128.82	107.50	16.56

Table 20. Br mass balance

Moisture Content	Bulk Density	Rep	Runoff	Retained by Soil	Retained by Sand	Sub-Surface Drainage	Total started	Total recovered	Difference
%	g/cm^3					kg/ha			
	1.81	1	15.10	10.59	2.91	7.36	42.62	35.95	15.65
10		2	18.71	10.49	2.49	8.19	39.97	39.88	0.21
		3	15.13	9.82	2.15	7.46	34.15	34.56	-1.20
	1.57	1	18.55	11.55	2.33	7.80	37.80	40.23	-6.45
10		2	16.49	9.91	2.25	8.03	39.97	36.68	8.22
		3	13.64	10.49	2.45	9.02	37.90	35.60	6.08
	1.33	1	17.85	10.31	2.36	7.82	37.80	38.35	-1.45
10		2	15.20	9.88	2.61	8.91	39.88	36.59	8.24
		3	16.16	9.66	2.19	10.06	37.90	38.07	-0.43
	1.10	1	14.35	11.06	3.14	6.82	33.45	35.37	-5.74
10		2	19.42	9.12	2.54	9.77	39.88	40.85	-2.45
		3	18.90	10.03	2.61	8.54	34.15	40.08	-17.37
	1.81	1	29.75	8.07	2.33	1.17	39.99	41.31	-3.31
15		2	20.88	9.35	2.61	2.07	38.86	34.91	10.14
		3	29.68	8.74	1.48	0.37	40.80	40.26	1.31
	1.57	1	24.01	9.42	2.34	1.87	38.13	37.65	1.26
15		2	27.51	9.75	1.84	1.16	38.86	40.27	-3.63
		3	22.87	9.50	3.49	2.68	40.79	38.54	5.52
	1.33	1	26.90	10.14	2.21	1.14	41.21	40.39	1.98
15		2	26.06	10.65	2.02	1.79	39.59	40.53	-2.36
		3	23.35	10.10	2.45	0.85	39.00	36.76	5.74
	1.10	1	27.28	9.36	2.14	2.65	38.13	41.43	-8.66
15		2	22.62	9.11	2.63	1.36	39.59	35.72	9.79
		3	27.69	9.50	1.78	0.72	38.99	39.69	-1.78

Table 21. Cl mass balance

Moisture Content	Bulk Density	Rep	Runoff	Retained by Soil	Retained by Sand	Sub-Surface Drainage	Total started	Total recovered	Difference
%	g/cm^3					kg/ha			
10	1.81	1	ND*	5.12	3.18	112.52	123.04	120.81	1.81
		2	ND	5.00	2.27	115.59	126.28	122.85	2.71
		3	ND	3.35	4.03	118.35	115.85	125.73	-8.53
	1.57	1	ND	6.93	3.12	119.20	126.21	129.24	-2.40
		2	ND	4.42	2.72	103.17	126.27	110.31	12.64
		3	ND	3.04	4.20	110.62	116.10	117.86	-1.52
	1.33	1	ND	4.21	4.96	100.15	126.21	109.33	13.38
		2	ND	1.53	2.27	116.57	124.67	120.38	3.44
		3	ND	2.19	1.21	107.77	115.78	111.17	3.98
	1.1	1	ND	3.44	5.72	117.65	123.04	126.82	-3.07
		2	ND	1.95	2.35	120.79	124.67	125.09	-0.34
		3	ND	1.86	3.28	108.24	115.41	113.38	1.76
10	1.81	1	ND	9.93	18.10	89.53	114.01	117.56	-3.12
		2	ND	6.91	14.14	91.22	117.28	112.27	4.28
		3	ND	21.65	53.90	41.04	123.18	116.59	5.35
	1.57	1	ND	9.07	21.48	84.87	116.22	115.42	0.69
		2	ND	16.30	41.49	55.80	119.55	113.59	4.99
		3	ND	6.19	15.85	100.08	123.18	122.12	0.86
	1.33	1	ND	7.95	25.03	83.82	114.76	116.81	-1.79
		2	ND	11.18	33.76	86.75	123.27	131.70	-6.84
		3	ND	8.87	31.69	77.94	123.32	118.50	3.91
	1.1	1	ND	7.90	22.03	86.05	116.22	115.98	0.21
		2	ND	13.26	24.60	89.78	124.00	127.64	-2.94
		3	ND	14.34	42.23	59.64	123.32	116.20	5.77

* ND=Not Detected

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